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RESEARCH MEMORANDUM

GROUND TESTS OF THE ELEVATOR POWER CONTROL SYSTEM AND FEEL DEVICE IN A BOEING B-47A AIRPLANE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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GROUND TESTS OF THE ELEVATOR POWER CONTROL SYSTEM AND FEEL DEVICE IN A BOEING B-47A AIRPLANE

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SUMMARY

Ground tests have been made on the longitudinal control system in a Boeing B-47A airplane. Part of the tests involved the use of a ground simulator which indicates to the pilot the short-period response of the airplane to elevator deflection. Frequency-response measurements were also made on the control system alone. These frequency-response data on the dynamic characteristics of the control system of a typical large airplane may be useful for application to autopilot design.

The simulator tests showed the pilot—airplane—control-system combination to be satisfactory in spite of the relatively large phase lags noticed in the frequency-response tests.

INTRODUCTION

The National Advisory Committee for Aeronautics has been testing power control systems for the prime purpose of determining the factors required for satisfactory operation. During the course of this study tests have shown that the characteristics of the power control system, such as servovalve friction, can influence the pilot—airplane—control-system combination to such an extent as to cause instability. A series of tests to study the effects of these characteristics are discussed at length in reference 1. As stated in reference 1, the instability involved has been extremely difficult to predict prior to flight tests. The need, therefore, for a reliable method of analysis based on ground tests or design estimates is immediately obvious. Two such methods have been tried on a fighter airplane and are described in reference 1. One of these, an analytical method, involves the combination of the frequency responses of the pilot, airplane, and control system. The other method involves a simple simulator designed to represent the response characteristics of the airplane being tested and afford the pilot visual indication of said response.

In order to provide additional information on the simulator, tests were made on the elevator power control system of a Boeing B-47A airplane while the airplane was being instrumented for loads and handling qualities flight tests. Frequency-response measurements were also made on the elevator control system not only to determine the dynamic characteristics of the system but also to aid in the analysis of the handling qualities flight tests. In addition the frequency-response data may be useful for application to autopilot design. Both the simulator tests and frequency-response tests were made over a large range of equivalent flight speeds. The purpose of this paper is to present the data obtained from the ground tests without detailed analysis.

POWER CONTROL SYSTEM AND FEEL DEVICE

Each control surface of the Boeing B-47A airplane is driven by its own power control unit consisting of a hydraulic jack and slide-type servovalve as described in reference 2. The power units are located as close as practical to their respective control surface with the aileron system using one unit in each wing. All power units are essentially identical with the exception that the elevator power unit also includes a restrictor that is controlled by impact pressure. Above about 300 knots the restrictor reduces the rate of flow of fluid in the return hydraulic line and hence the rate of control surface motion available.

Figure 1 shows a schematic drawing of the elevator power unit. In the figure the lock and bypass valve is shown in the position assumed when there is no hydraulic pressure in the system. This position opens each side of the power cylinder to the return line to the reservoir in the system. This arrangement in addition to the necessary mechanical linkages affords the pilot manual control when hydraulic pressure is lost. When pressure is on the system the bypass valve is held closed (compressing the spring) by the hydraulic pressure. The metering control valve then routes the high pressure fluid to the appropriate side of the power cylinder and opens the other side of the cylinder to the return hydraulic line. As can be seen in figure 1 the valve body is connected to the control surface and, therefore, serves as the feedback link that closes the valve when the control surface reaches the position called for by a given valve displacement.

The ground tests were made only on the elevator system because previous experience in addition to reference 1 has shown that the elevator control is the most sensitive to effects such as valve friction. For this reason, all of the following discussion will deal only with the elevator control system.

The elevator feel forces are derived from an air bellows which supplies forces that vary directly with impact pressure and stick deflection. A schematic drawing of the feel device is shown in figure 2. The feel device is located near the power control unit and is connected to the pilot's control through a cable system. The Q-spring, as shown in figure 2, is connected to the primary cable system by a dual cable arrangement in order to provide a higher centering force gradient for small control deflections. This centering arrangement resulted in slightly lower slopes of stick force against elevator angle for down elevator than for up elevator because of the difference in mechanical advantage of the system. An air compressor was used in the ground tests to apply the equivalent impact pressure to the bellows for each test speed. The impact pressure was also applied to the restrictor so that the effect of the restrictor would be in the results.

A ground calibration of the feel device was performed by setting various airspeeds on the feel system as previously described and moving the control column slowly through the deflection range. The frequency of this control manipulation was about 0.02 cycle per second and will be referred to as the static calibration. The airspeed range covered was from 0 to 518 miles per hour.

A schematic drawing is presented in figure 3 which shows the general layout of the elevator control system and relative location of power control and feel device.

APPARATUS AND TESTS

Frequency-response data of the control system were obtained by oscillating the pilot's stick sinusoidally with an electric motor. The maximum frequency obtainable with the motor was approximately $1\frac{3}{4}$ cycles per second. This maximum frequency was considered to be sufficiently high because previous experience, in addition to reference 1, has indicated that the instability involving pilot, airplane, and control system generally occurs at frequencies below 1 cycle per second. The lowest frequency tested was approximately 1/10 cycle per second.

Standard NACA recording instruments were used to measure stick angle, stick force, elevator angle, and servovalve displacement.

Several runs were made using a ground simulator. The simulator consisted simply of a projector mounted on pivots and equipped with springs and damping so that its period and damping characteristics simulated those of the short-period longitudinal motion of the airplane. The setup was similar to that shown in figure 4. The period and damping of the simulator were adjusted to equivalent airplane values for the test conditions. During these tests, the simulator displacement was also measured in addition to the previously mentioned quantities.

All of the ground tests were made with no load on the control surface. The application of loads similar to those encountered in flight would probably reduce somewhat the amplitude ratios between elevator angle and control inputs because of elevator twist or deflection of the linkages between the elevator and the power control cylinder in the frequency range investigated. Very little effect of such loads on the phase angles would be expected in the frequency range investigated because of the large stiffness of the system beyond the power control unit.

The data were obtained at six different simulated speeds, from 0 mile per hour to 500 miles per hour in increments of 100 miles per hour by exerting the equivalent air pressure on the Q-spring of the feel device.

Complete tests were made with four different amplitudes of stick motion by adjusting the linkages between the driving motor and pilot's stick. Various amplitudes were tested because in nonlinear systems the amount of stick motion can influence the performance of power control systems.

Examples of some test records are shown in figure 5. As can be seen in figure 5, the force and elevator angle records are not perfect sine waves. All such records were transformed into equivalent sine waves by means of the method described in reference 3.

RESULTS AND DISCUSSION

The results of the static force calibration are presented in figures 6 and 7. The data shown in figure 6 indicate a friction band of approximately ±8 pounds. The action of the centering system is evident particularly at the higher speeds. Also shown are the slightly different stick force gradients for down elevator than for up elevator resulting from the geometry of the system shown in figure 2.

Amplitude ratios and phase angles of the control system alone are presented in frequency-response form in figures 8, 9, and 10. Figure 8 shows the relation between elevator angle and stick force for the four stick amplitudes over the test speed range. The relation between elevator angle and stick force may be considered to be made up of two components, the variation of stick angle with stick force and the variation of elevator angle with stick angle. In order to facilitate the examination of the effect of each component, these variations are also shown in figures 9 and 10, respectively.

In figures 11, 12, and 13, the data for amplitude ratios and phase angles have been cross plotted as functions of stick amplitude for selected values of frequency and airspeed. These plots are used as the basis of the subsequent discussion.

Relation between elevator angle and stick force.- Figure 11 shows the amplitude ratio and phase angle between elevator angle and stick force as a function of stick amplitude for the highest and lowest speeds tested and for frequencies of 0.1 and 1.6 cycles per second. Throughout the frequency range, the phase angles between elevator angle and stick force are relatively large. Also at all frequencies the phase angles seem almost independent of speed until the stick amplitude reaches values above $\pm\frac{1}{2}^{\circ}$. As the stick amplitude increases still further, the speed effect becomes more noticeable. At all speeds, an increase in stick amplitude results in an increase in amplitude ratio of elevator angle to stick force.

Some explanation of the trends shown in these results may be made by considering the contribution of the previously mentioned components that make up the overall result.

Relation between stick angle and stick force.- The relation between stick angle and stick force is presented in figure 12. For the lowest stick amplitude tested, the amplitude ratios of stick angle to stick force show very little change either with speed or frequency. Also, the phase lag between stick position and stick force is small and practically constant over the frequency range. This result might be expected if the friction existing in the pulleys and bell-cranks in the rear part of the fuselage effectively restrained the motion of the system at this point for very small stick motion. Most of the force on the stick under these conditions would result from stretch of the long control cables between the control wheel and the rear part of the fuselage. The records of servovalve displacement also showed that the motion transmitted to the valve was smaller than the motion that would be expected with a system with linear characteristics. The valve movement which did occur was smooth, however, which indicates that the valve friction was mainly of the viscous type rather than the static type. At larger amplitudes and low values of airspeed, the motion of the control cables is sufficiently large to cause appreciable movement of the input of the power control unit, with the result that frictional forces in the control system become predominant. As a result, the ratio of stick movement to stick force is increased and the phase lag approaches the expected 90°. Also at the lower speeds, the phase lag shows consistent increase with increase of amplitude and frequency of stick input possibly as a function of the change of momentum of the control column and related masses. With increasing airspeed, the spring restraint applied by the feel device is superimposed on the frictional forces, causing less phase lag. The greater amplitude ratios of stick angle to stick force at the larger stick amplitudes at a given airspeed is probably caused by the nonlinear restraint applied by the feel device. This device, as was mentioned previously, applies an increased centering force gradient at small deflections.

Relation between elevator angle and stick angle.- Figure 13 shows the relation between elevator angle and stick angle. For the smallest stick motions, the small movement of the input to the power control system is again shown by the reduced amplitude ratio of elevator angle to stick angle and the large phase lag between elevator angle and stick angle. The large increase in phase angle with frequency may also result from the valve characteristics.

At larger stick amplitudes, the phase lag introduced by the power control unit becomes more consistent and is practically unaffected by amplitude or airspeed setting. Increasing the airspeed, however, reduces the amplitude ratio of elevator angle to stick angle because of stretch in the control system. For the largest test amplitude, the ratio of elevator angle to stick angle approaches the static gearing ratio of approximately 1.3 at the low frequencies. Throughout the tests, no effects of the restrictor were apparent.

Simulator tests.- It should be pointed out that the simulator tests give an indication of the stability of the pilot—airplane—control-system combination whereas the frequency-response tests previously discussed involve only the control system. At present the simulator has been used only on three control systems, each system being judged solely on whether or not the pilot could position the light spot on the specified line. The simulator results along with flight tests have shown that a very broad classification of either satisfactory or unsatisfactory has been sufficient thus far. Further research is necessary in order to establish the degree of stability that can be determined from the simulator tests. On the basis of previous tests, however, if the pilot cannot readily position the light spot on the specified line, similar positioning difficulties will be present in flight when the pilot attempts to establish a given acceleration or speed.

Several runs were made using the ground simulator with several different pilots. The simulator is designed so that changes in normal acceleration are approximated by the motions of the light projector shown in figure 4. These motions are recorded continuously and are also indicated to the pilot by the light spot projected on the screen. During these tests the pilots were instructed to move the light spot as rapidly as possible from one specified line of the screen to another. The lines were mounted on the screen to represent predetermined amounts of normal acceleration change. Records were obtained for various airspeeds and various amounts of equivalent normal acceleration.

In the simulator tests the pilots performed pull-ups from trim; therefore, in order to hold the light spot on the specified line, a pull force well away from trim was required. In the frequency-response tests previously discussed, the stick was oscillated about trim. It is conceivable that this difference in testing procedure could cause a slight difference between the results of the frequency-response tests and the simulator. Some frequency-response runs however were made about an out-of-trim point and compared with the oscillations about trim. The measured differences were not felt to be large enough to affect the results quantitatively. Figure 14 shows typical records obtained from the simulator runs that were made at an equivalent airspeed of 250 miles per hour. For this speed, the natural frequency of the simulator was adjusted to be about 1/6 cycle per second and the damping ratio was about 0.50 critically damped. Figure 14(a) shows the results when the smallest test amplitude of acceleration (1/3g) was specified, figure 14(b) shows the results from a medium acceleration change (1g) and figure 14(c) shows the largest test amplitude (2g). As can be seen from the figures, the pilot had no difficulty in positioning the light spot on the proper line. This indicates that the pilot—airplane—control-system combination is satisfactory. Similar results were observed for a test speed of 145 miles per hour with the same acceleration amplitudes. For the tests at 145 miles per hour the natural frequency of the simulator was changed to about 1/10 cycle per second and the damping ratio was held approximately constant at 0.50 critically damped. In order to provide a comparison with the characteristics of some unsatisfactory control systems, these data may be compared with the results presented in figure 19 of reference 1.

CONCLUDING REMARKS

The simulator results indicated that the pilot—airplane—control-system combination would be satisfactory in flight in spite of the relatively large phase lags measured in the frequency-response tests of the control system.

The large phase lags measured in the frequency-response tests existed throughout the frequency range between elevator angle and stick force, and between elevator angle and stick angle. These lags were decreased when the input amplitude was increased. The results also showed that the ratio of output to input increased as the stick amplitude was increased through the range of small amplitudes tested. Beyond this range of amplitudes, the ratio approached the static gearing ratio.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 22, 1954.

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1. Phillips, William H., Brown, B. Porter, and Matthews, James T., Jr.: Review and Investigation of Unsatisfactory Control Characteristics Involving Instability of Pilot-Airplane Combination and Methods for Predicting These Difficulties From Ground Tests. NACA RM L53F17a, 1953.

2. Anon.: Handbook Erection and Maintenance Instructions - USAF Model B-47A Aircraft. AN 01-20ENA-2, U. S. Air Force, Aug. 1, 1950. (Rev. July 1, 1953.)

3. Jones, Robert T., and Sternfield, Leonard: A Method For Predicting the Stability in Roll of Automatically Controlled Aircraft Based on the Experimental Determination of the Characteristics of an Automatic Pilot. NACA TN 1901, 1949.

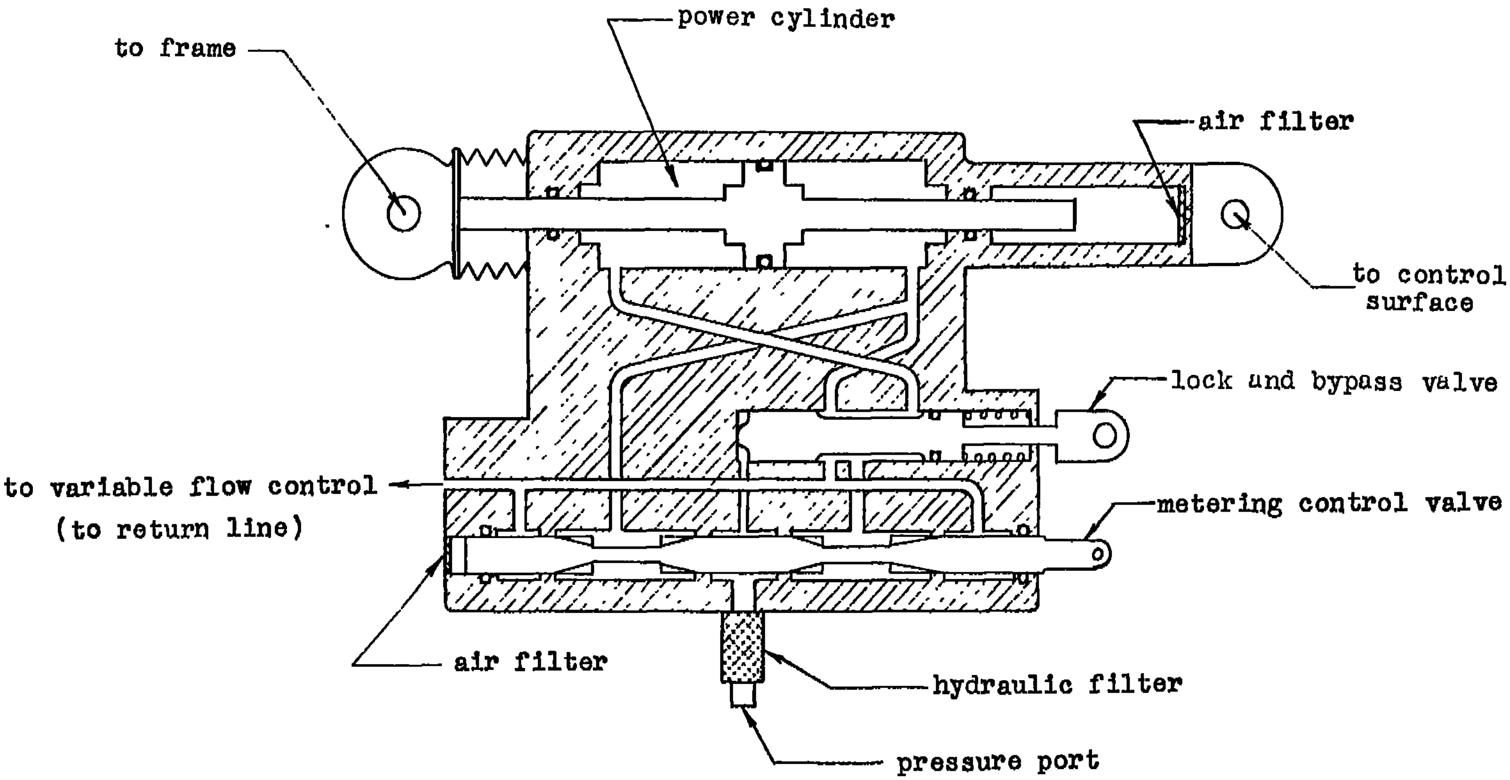


Figure 1.- Schematic diagram of elevator power unit.

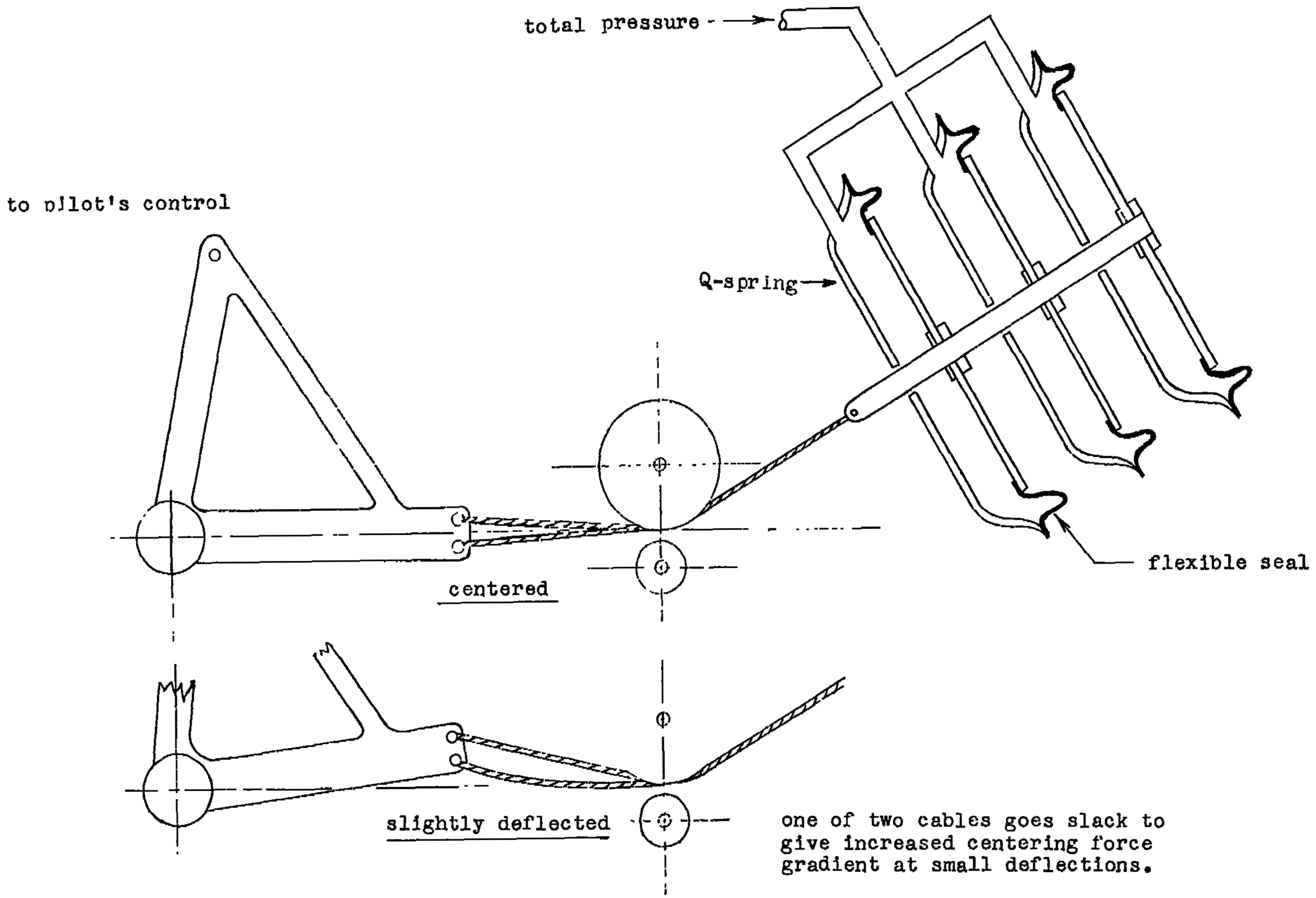


Figure 2.- Schematic diagram of elevator feel device.

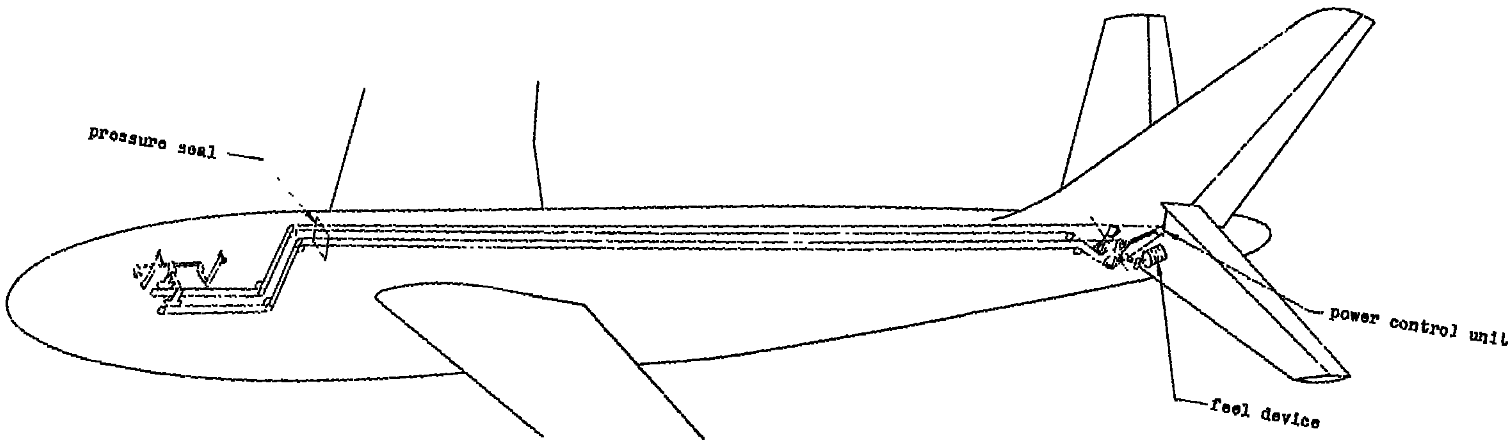


Figure 3.- Schematic diagram of elevator control system.

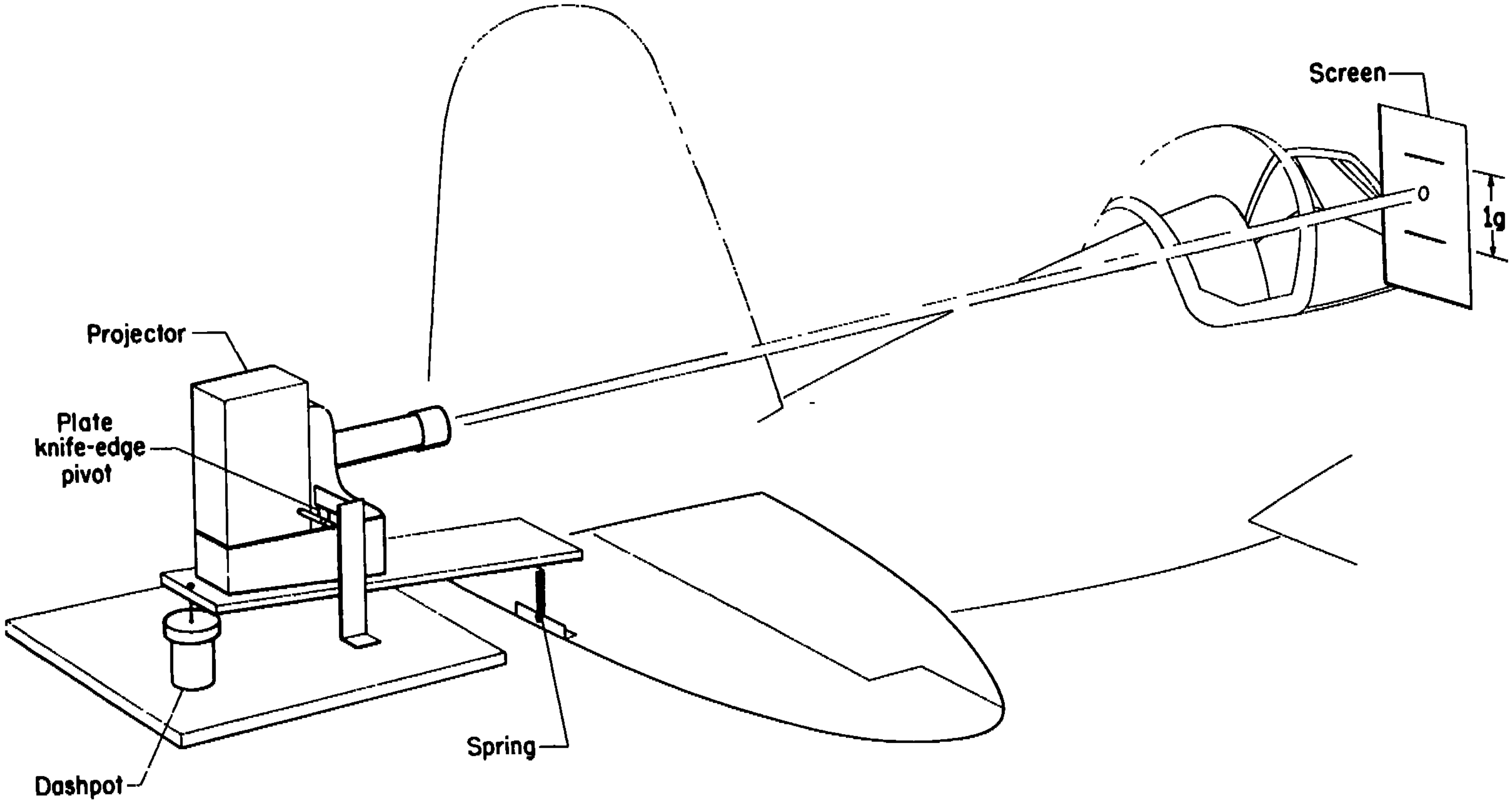


Figure 4.- Schematic diagram of ground simulator setup.

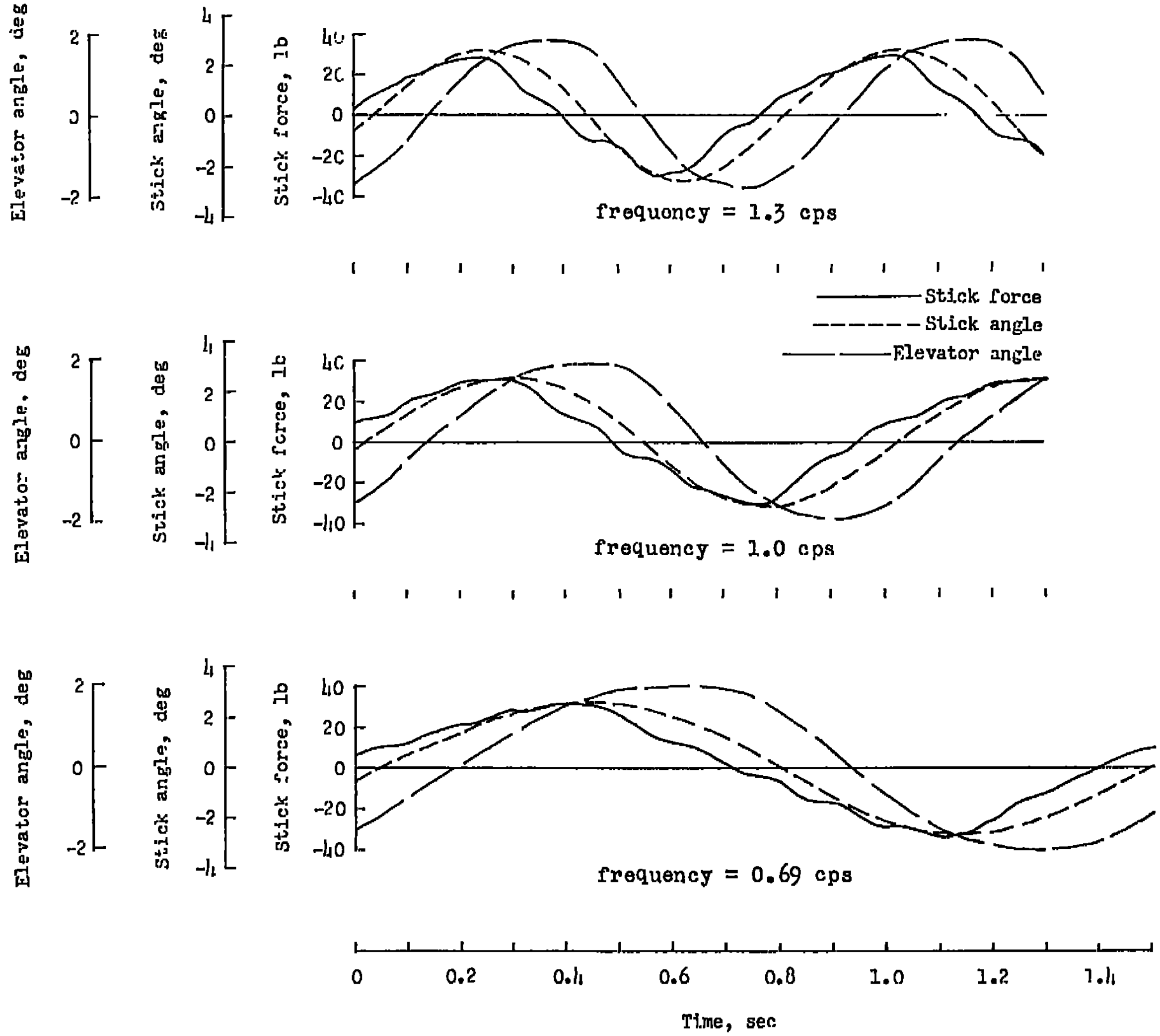
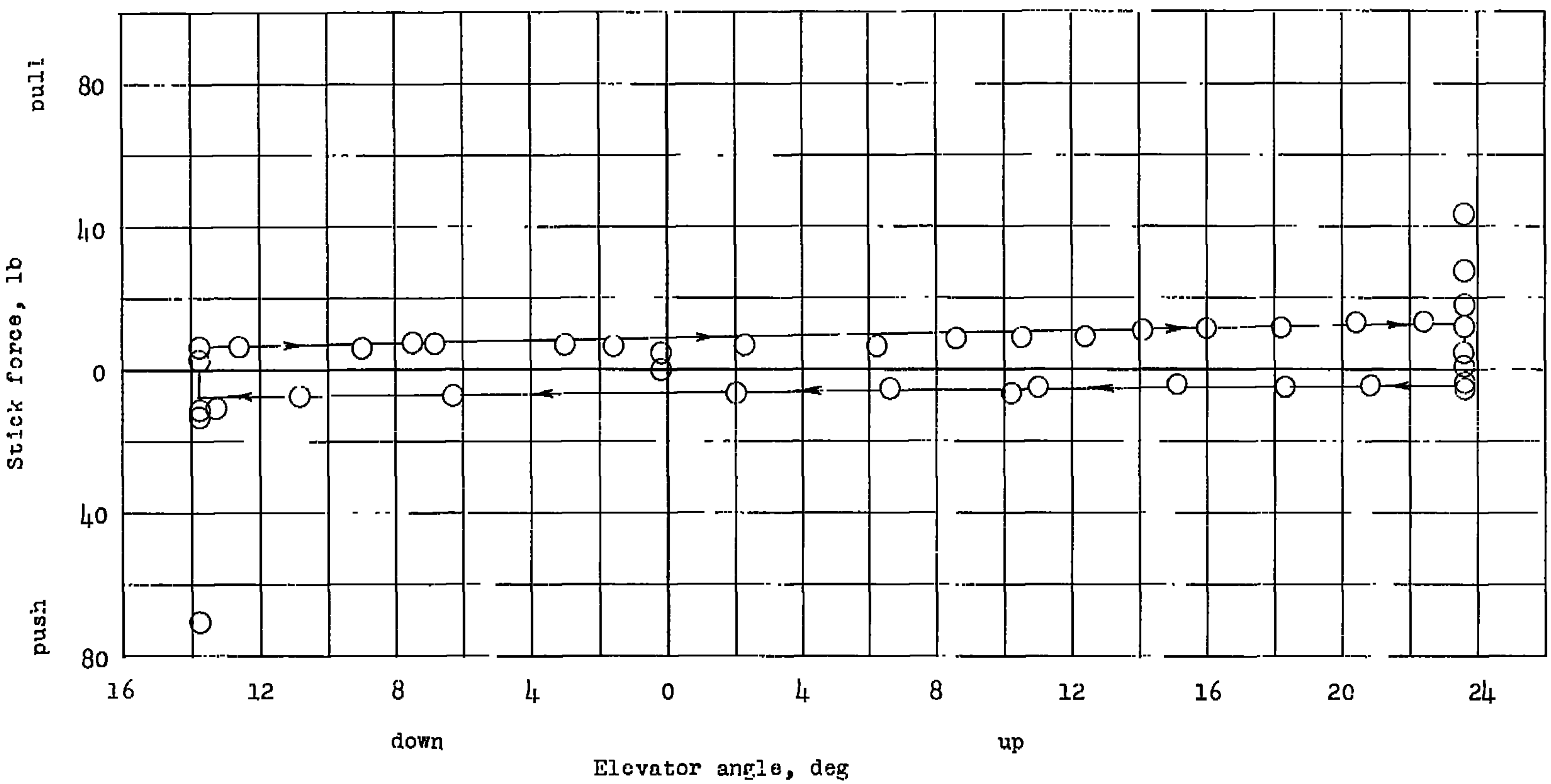


Figure 5.- Typical records from ground tests showing relationship between stick force, stick angle, and elevator angle for three different frequencies. Stick amplitude, $\pm 2\frac{1}{2}^{\circ}$, equivalent airspeed, 300 mph.

[redacted]



(a) Airspeed, 0 mph.

Figure 6.- Variation of stick force with elevator angle.

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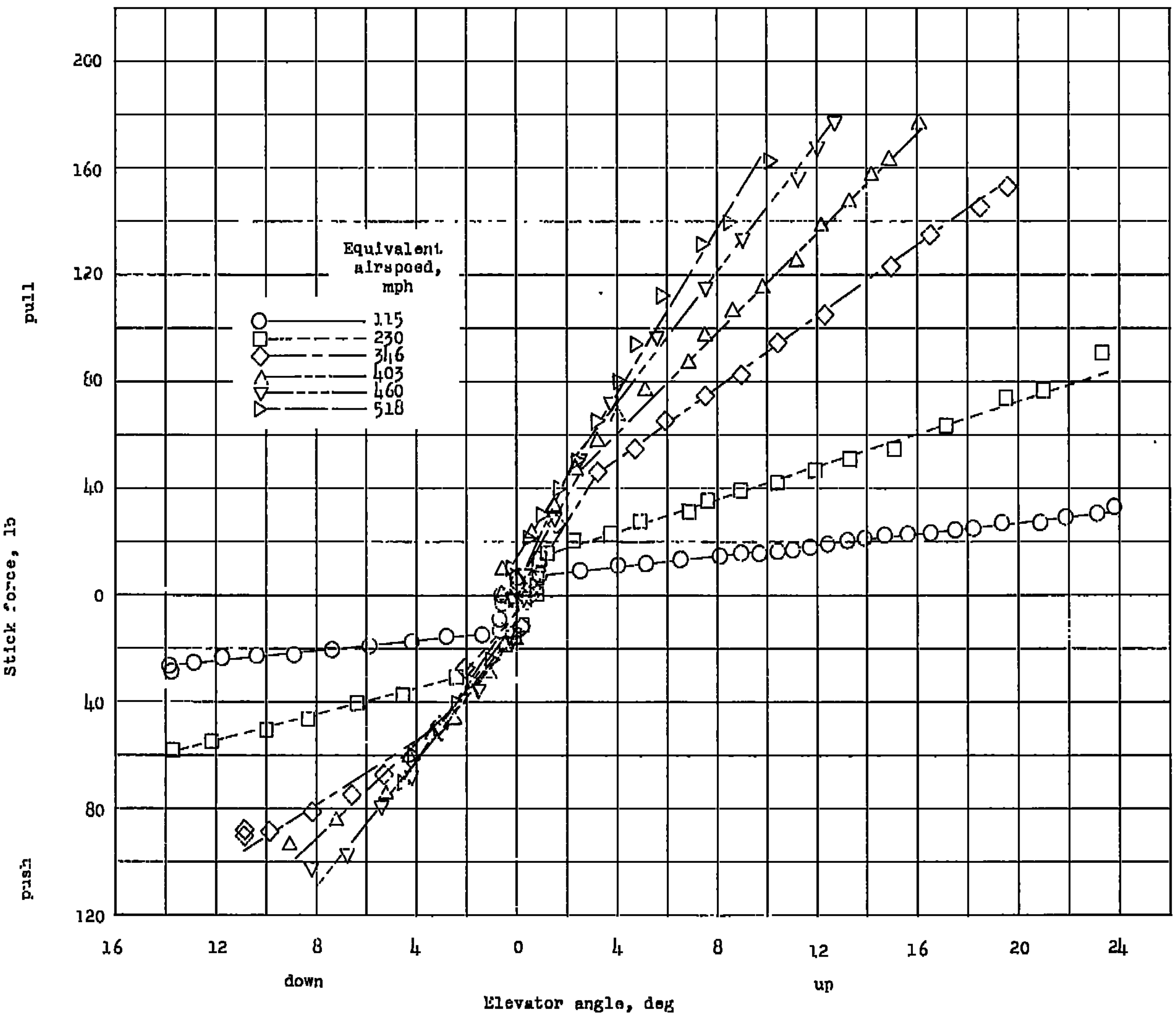
[redacted]



(b) Airspeed, 115 to 518 mph.

Figure 6.- Concluded.

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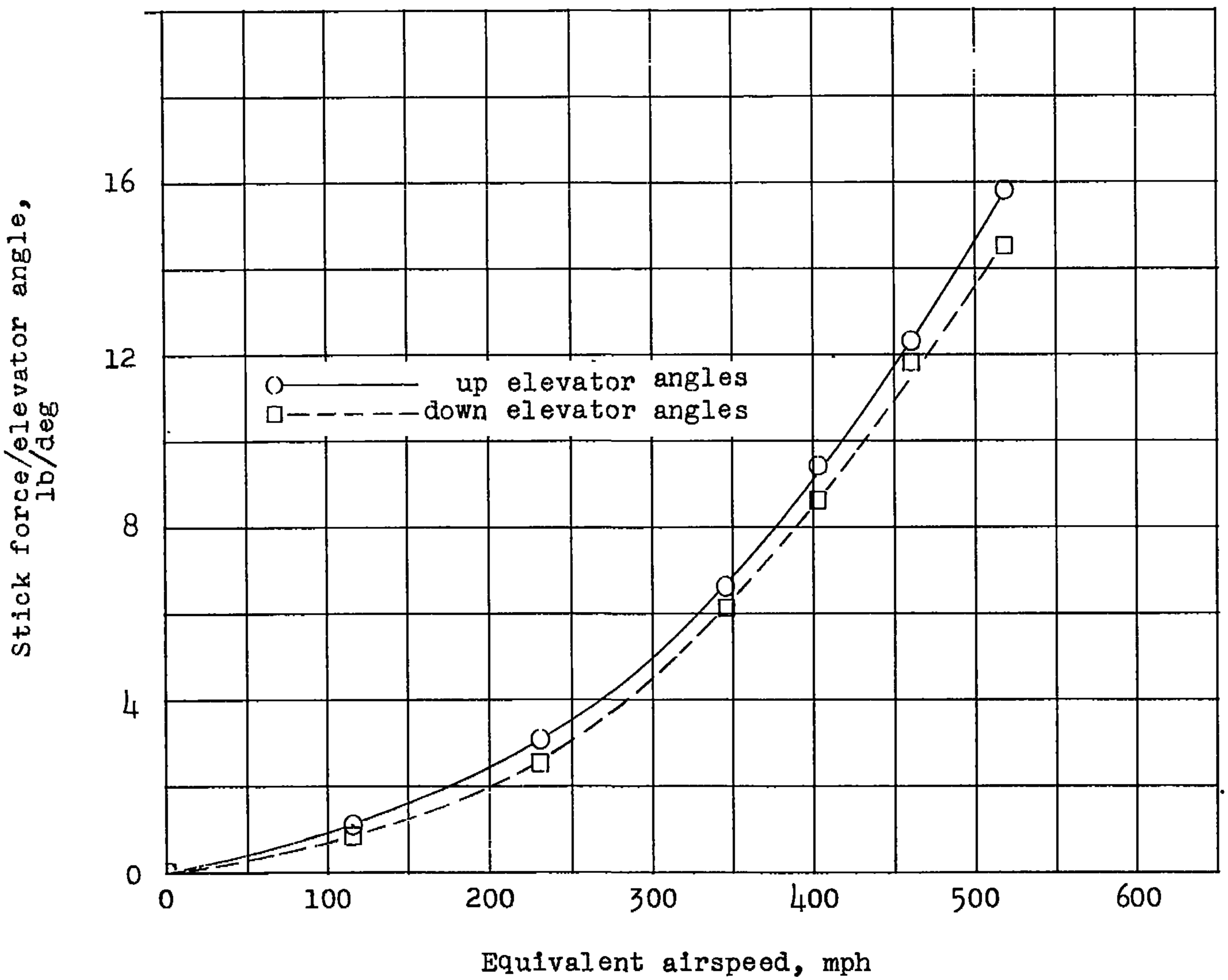
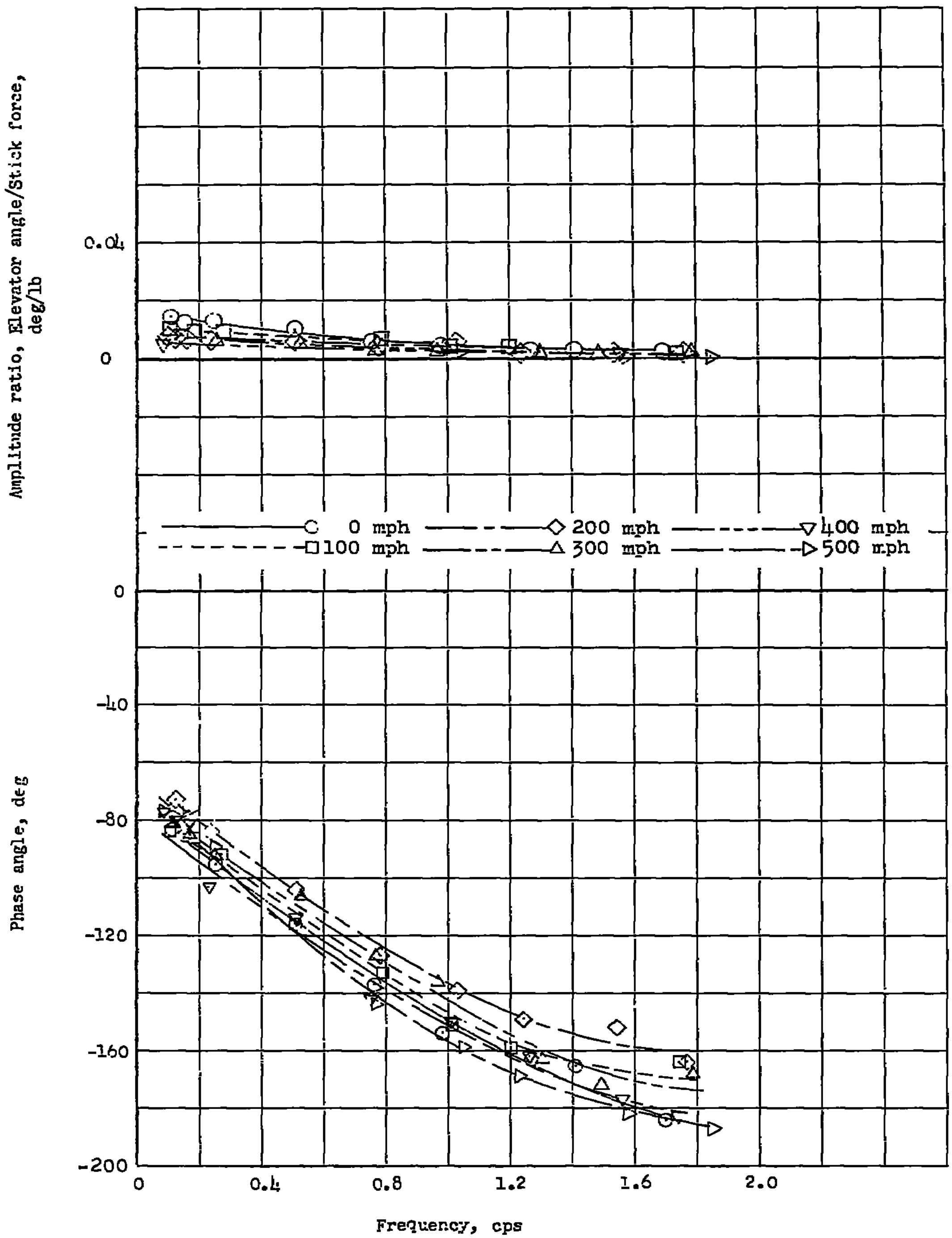


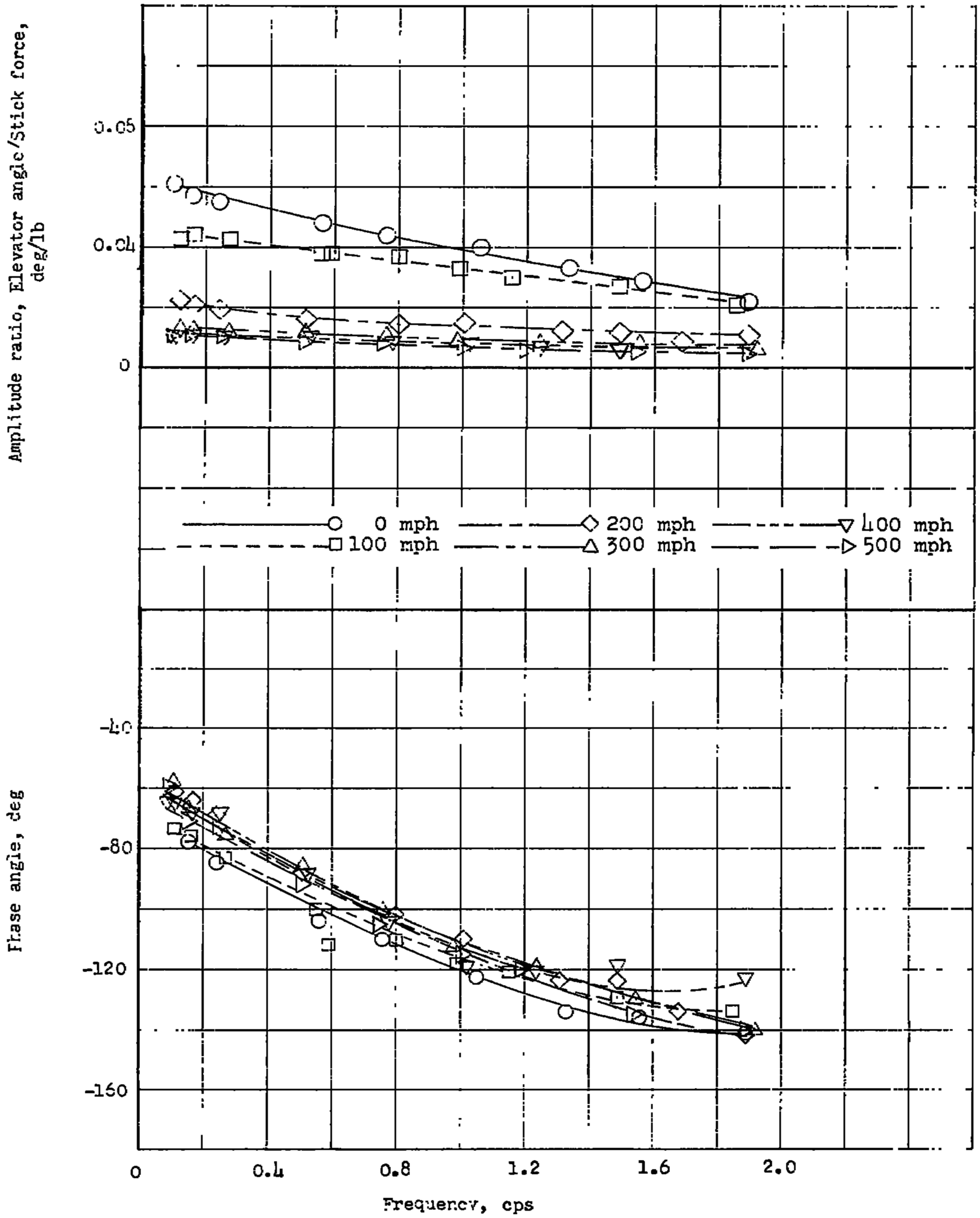
Figure 7.- Variations of stick force per degree of elevator angle as provided by the feel device for various airspeeds. All slopes measured in linear range occurring beyond ±3° elevator angle.

[redacted]



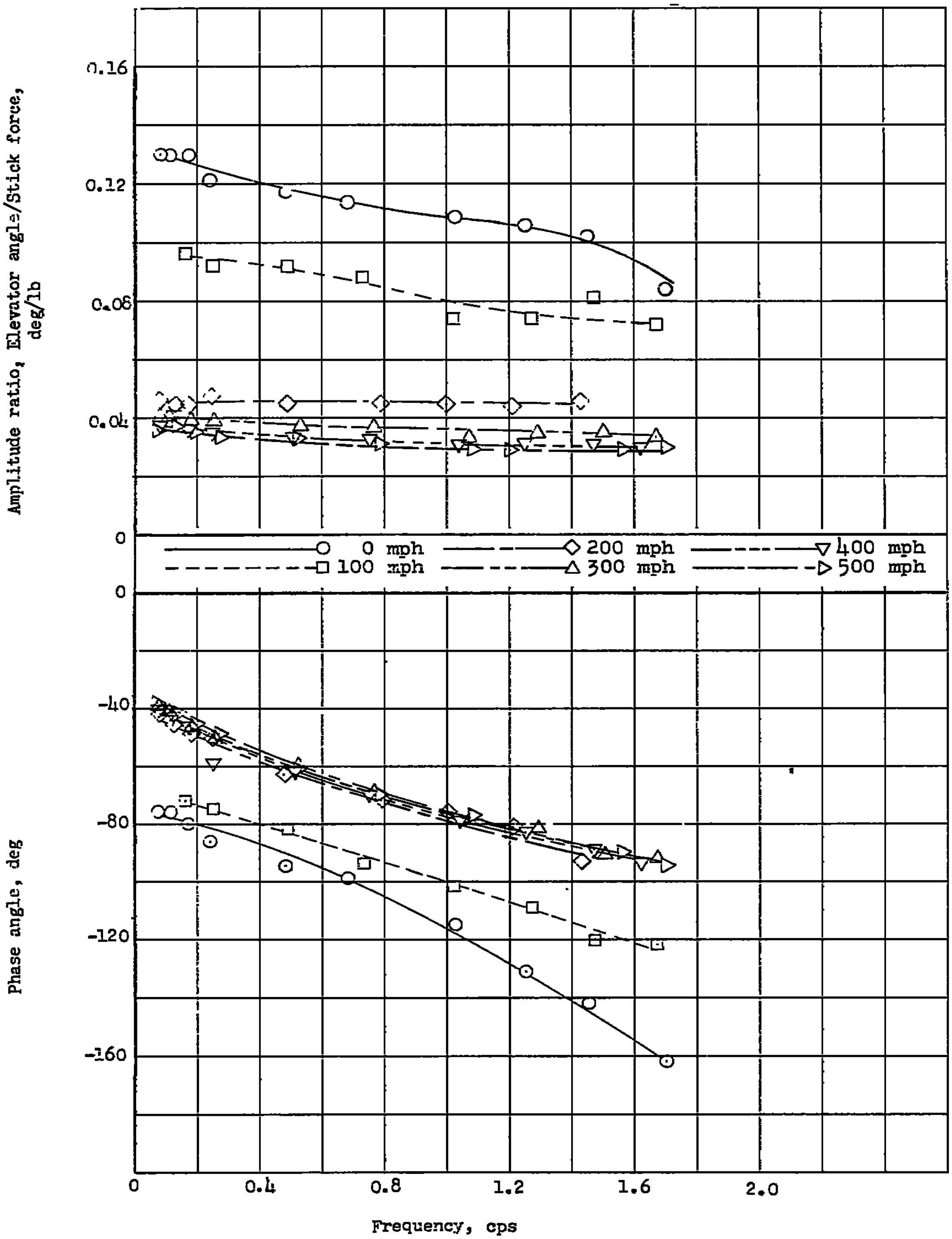
(a) Stick amplitude, $\pm\frac{1}{4}^{\circ}$.

Figure 8.- Frequency response relationship between elevator angle and stick force.



(b) Stick amplitude, $\pm\frac{1}{2}^{\circ}$.

Figure 8.- Continued.



(c) Stick amplitude, $\pm 1\frac{1}{2}^{\circ}$.

Figure 8.- Continued.

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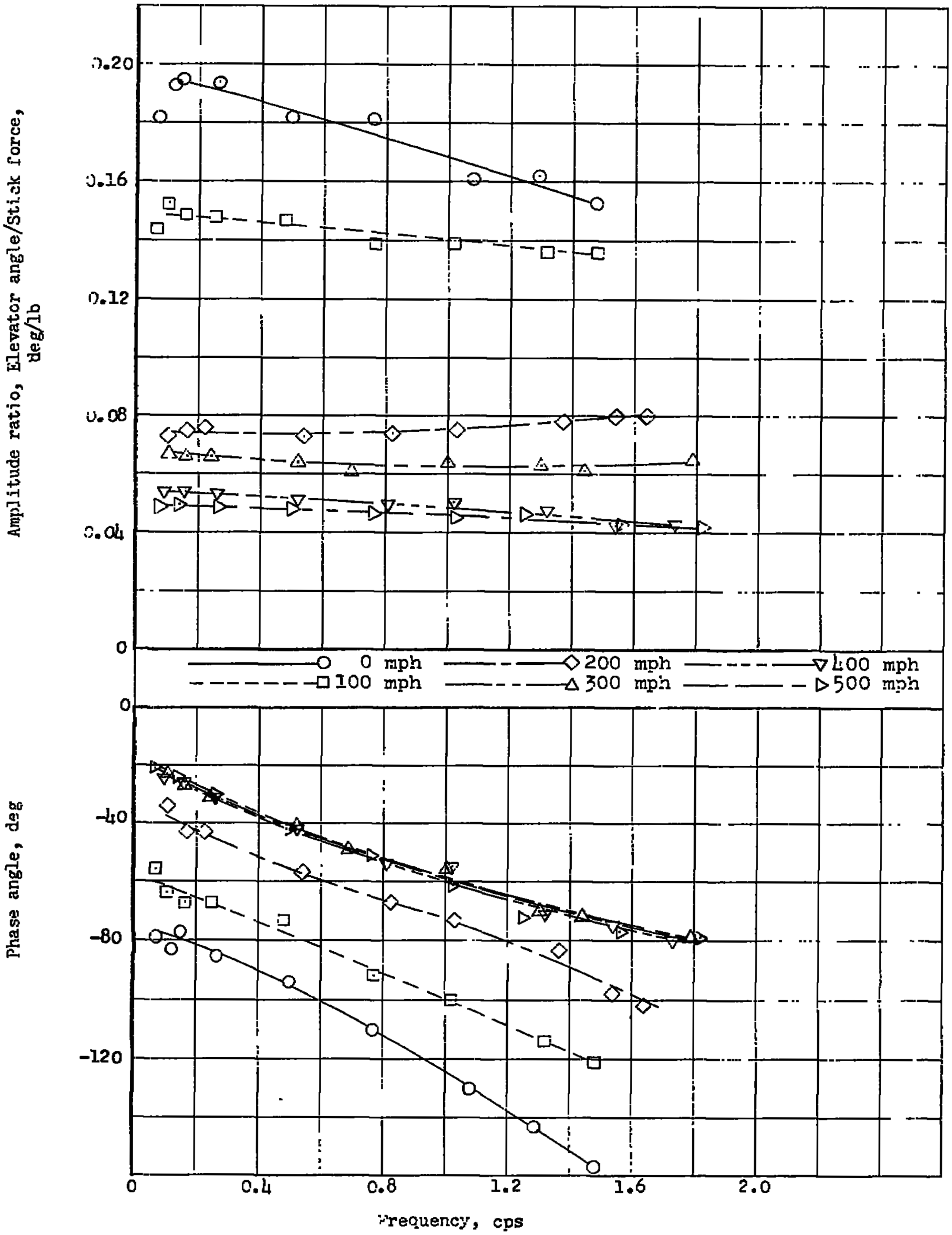
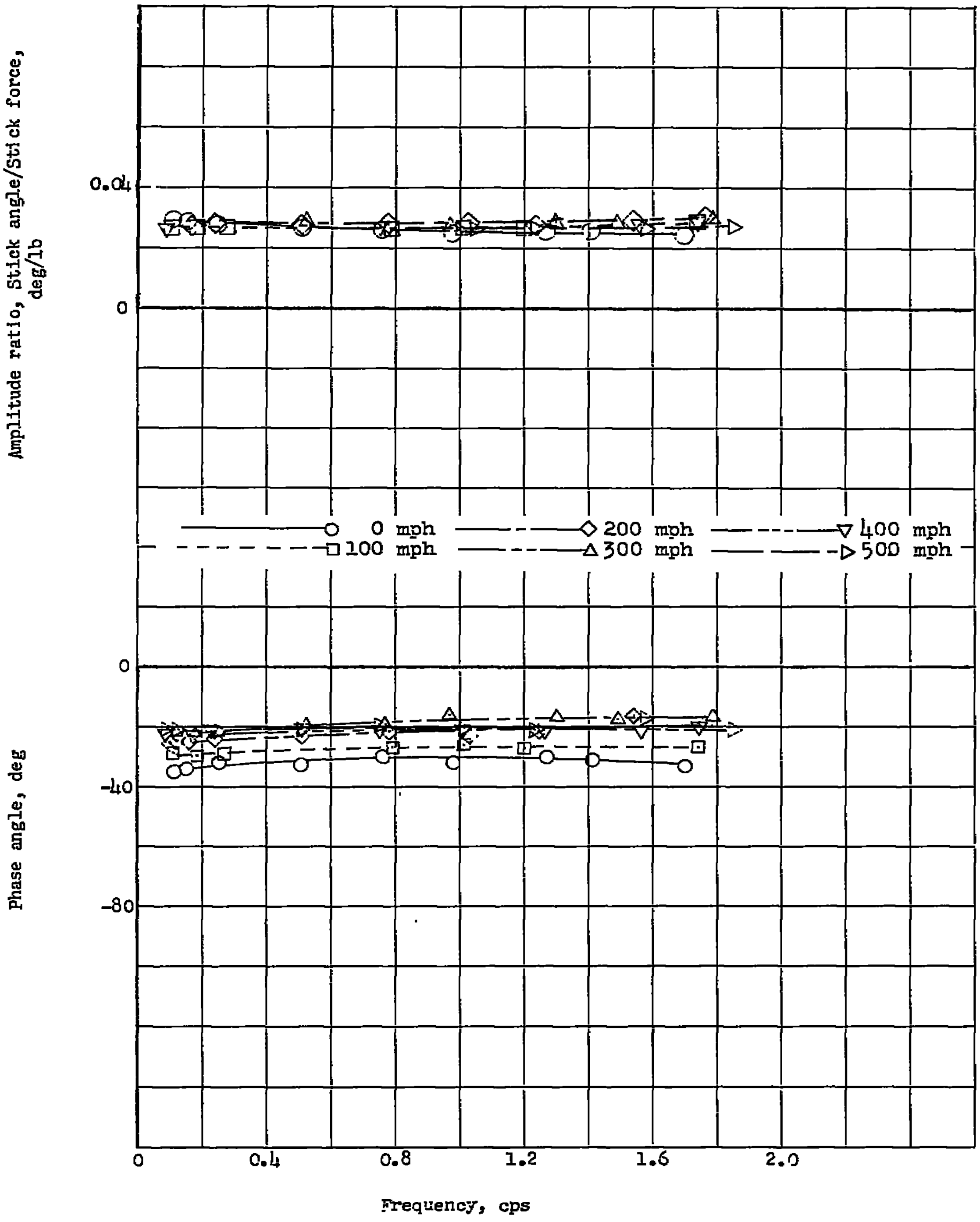


(a) Stick amplitude, $\pm 2\frac{1}{2}^{\circ}$.

Figure 8.- Concluded.



(a) Stick amplitude, $\pm\frac{1}{4}^{\circ}$.

Figure 9.- Frequency response relationship between stick angle and stick force.

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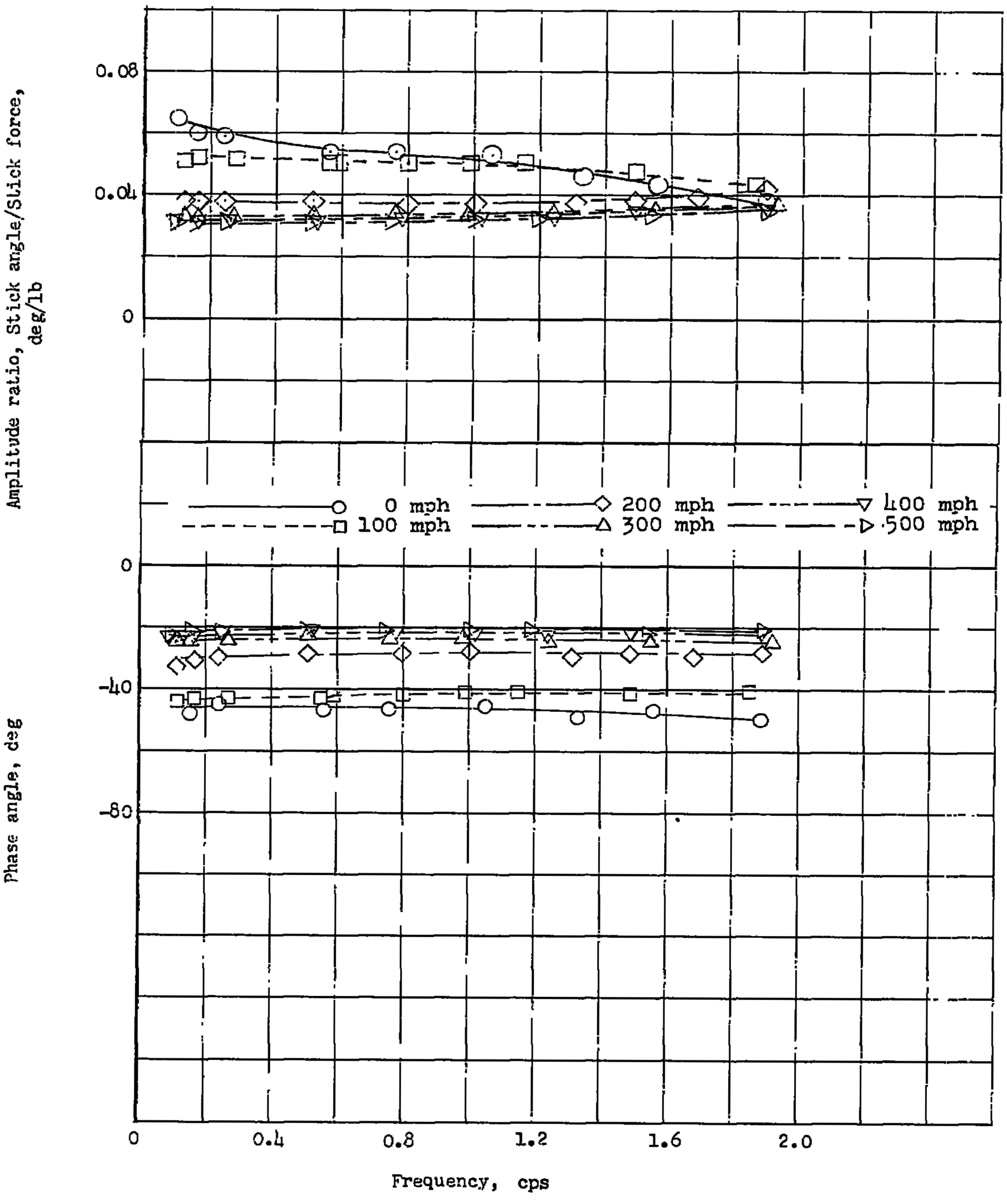
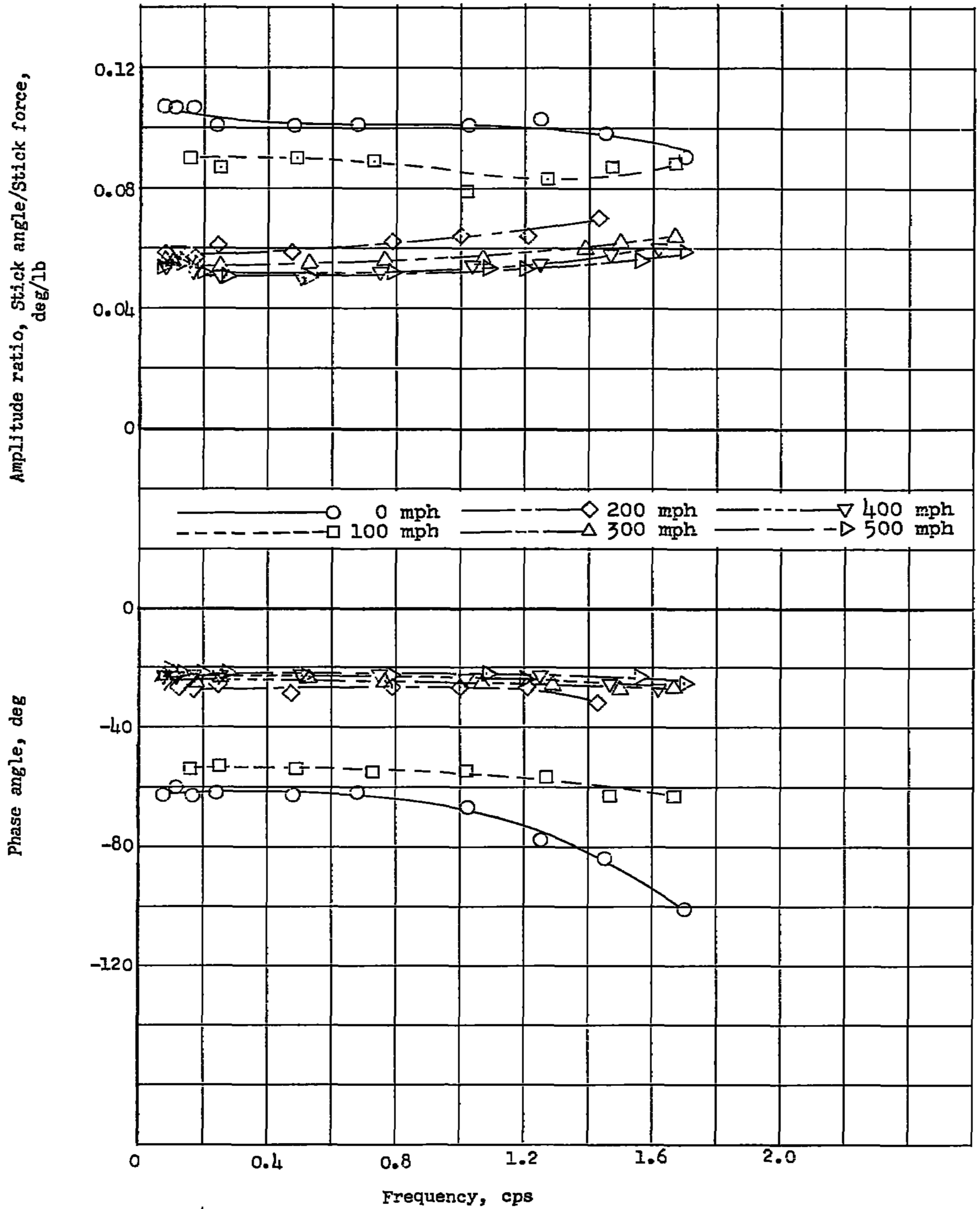


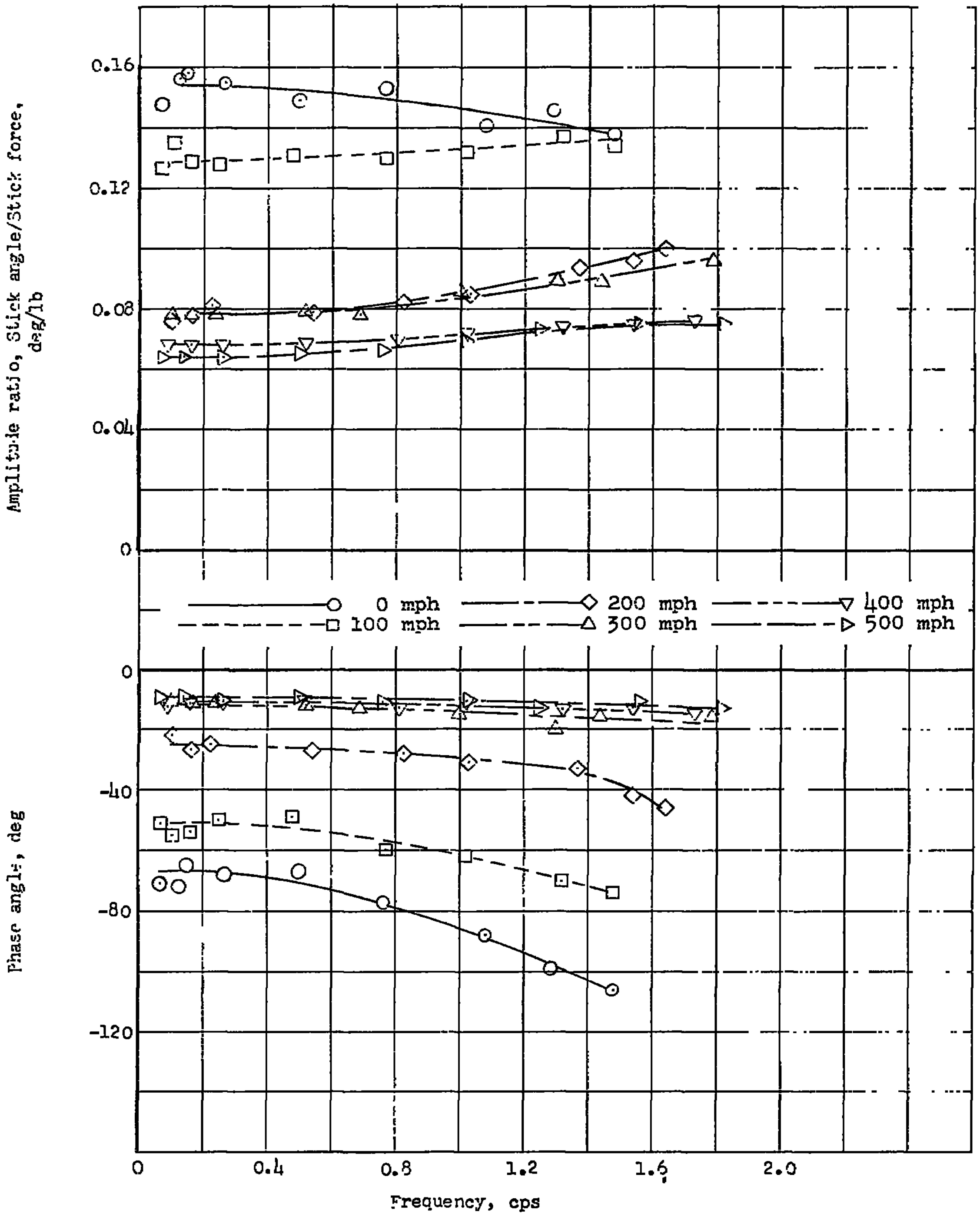
(b) Stick amplitude, $\pm\frac{1}{2}^{\circ}$.

Figure 9.- Continued.



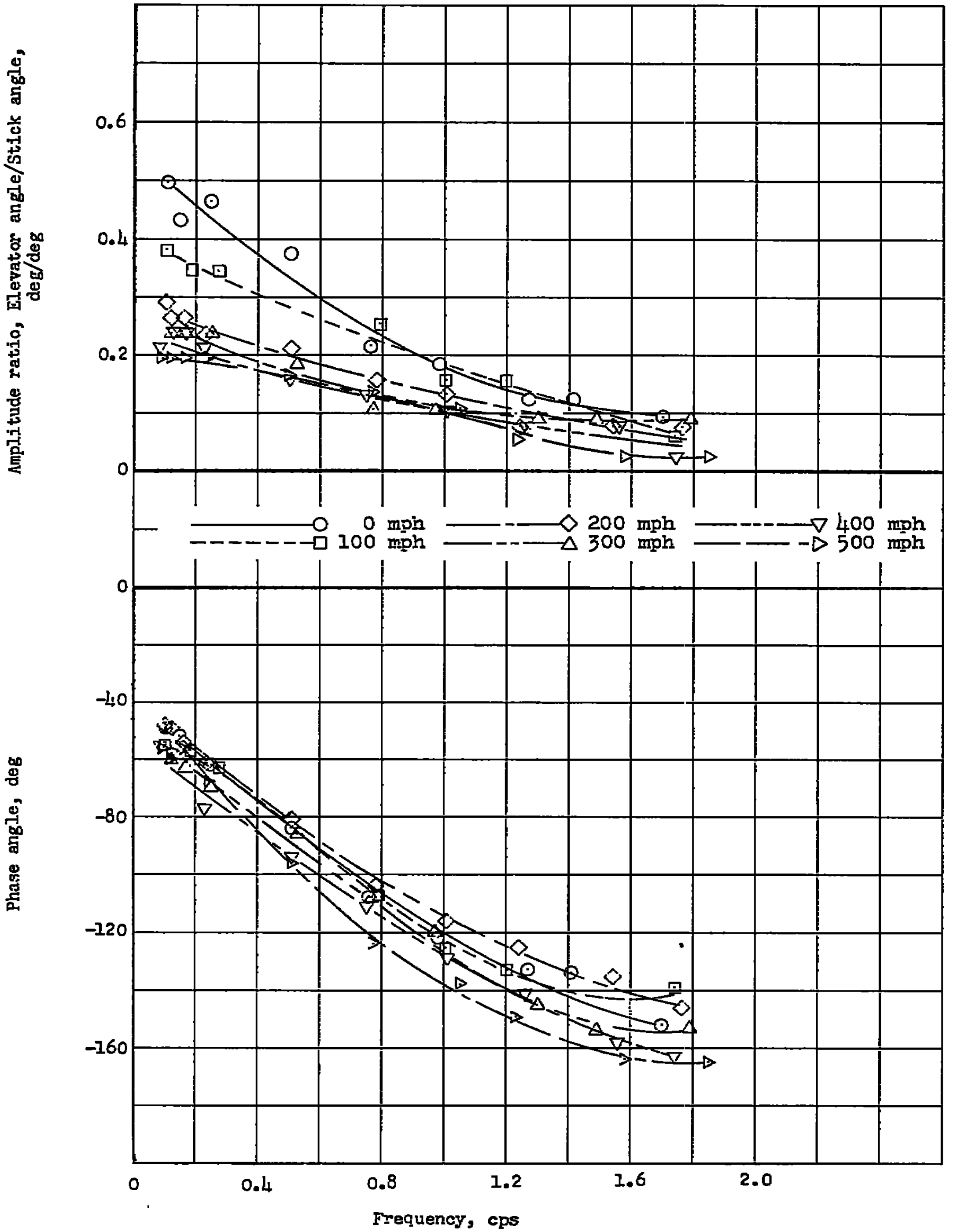
(c) Stick amplitude, $\pm 1\frac{1}{2}^{\circ}$.

Figure 9.- Continued.



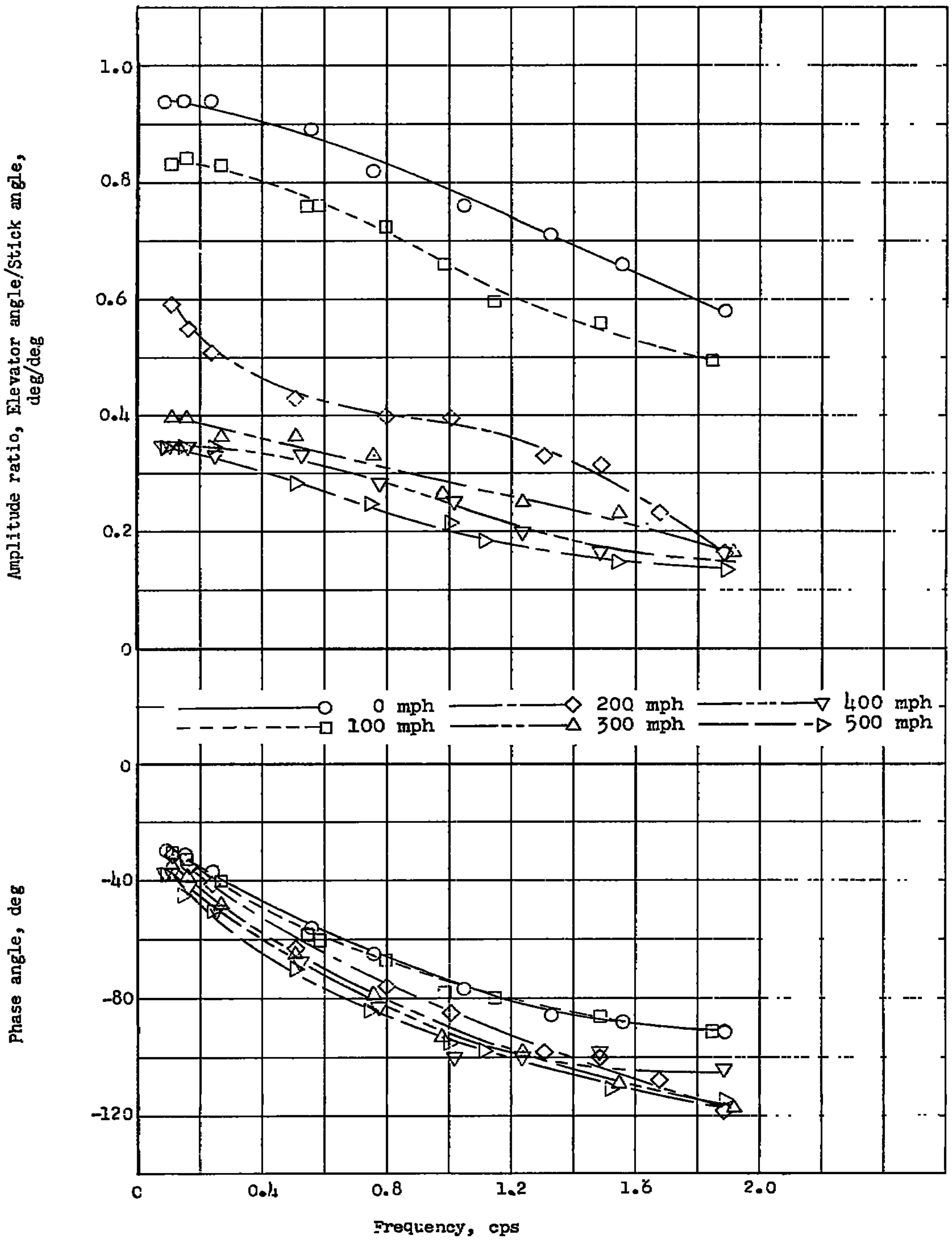
(d) Stick amplitude, $\pm 2\frac{1}{2}^{\circ}$.

Figure 9.- Concluded.



(a) Stick amplitude, $\pm\frac{1}{4}^{\circ}$.

Figure 10.- Frequency response relationship between elevator angle and stick angle.



(b) Stick amplitude, $\pm\frac{1}{2}^{\circ}$.

Figure 10.- Continued.

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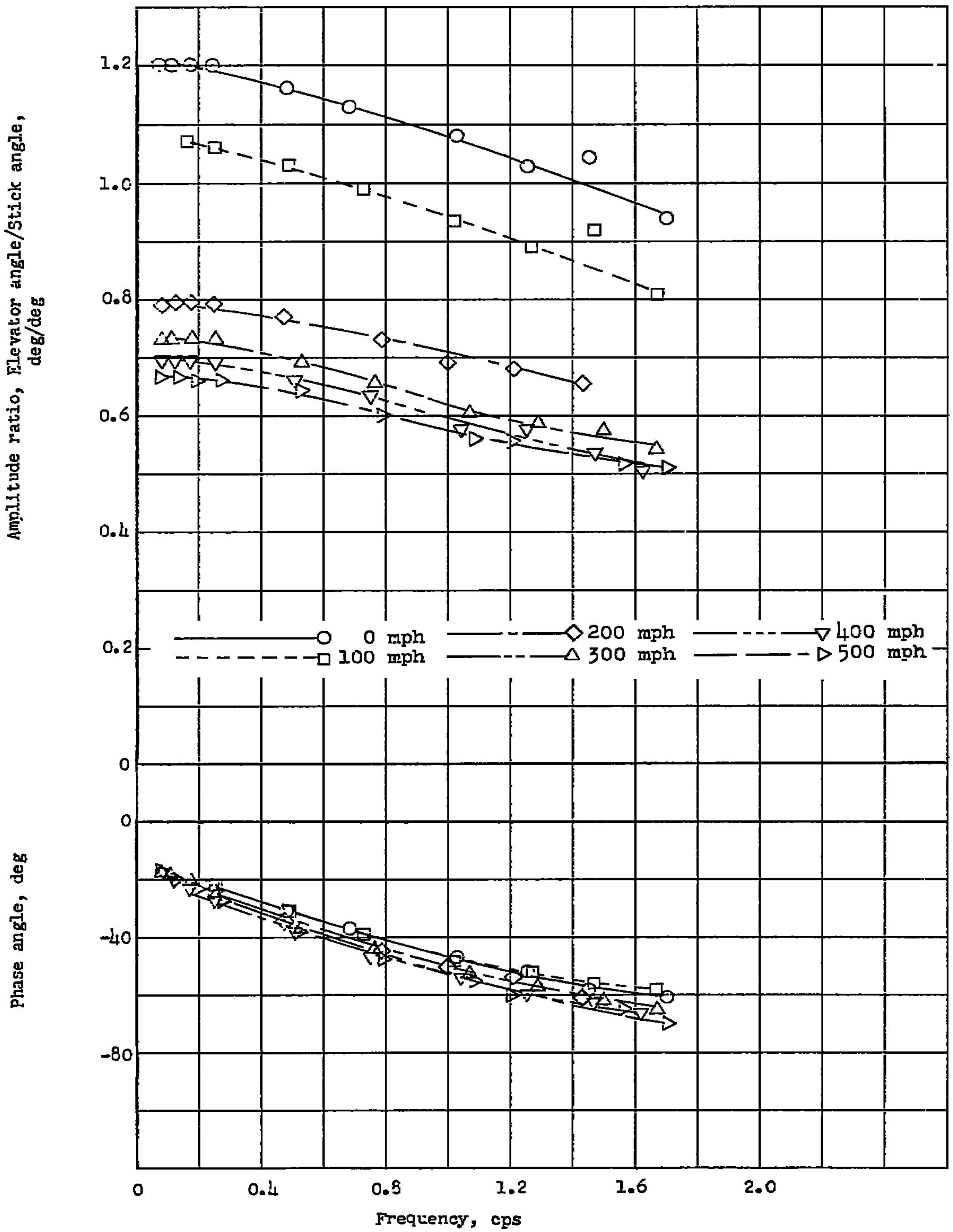
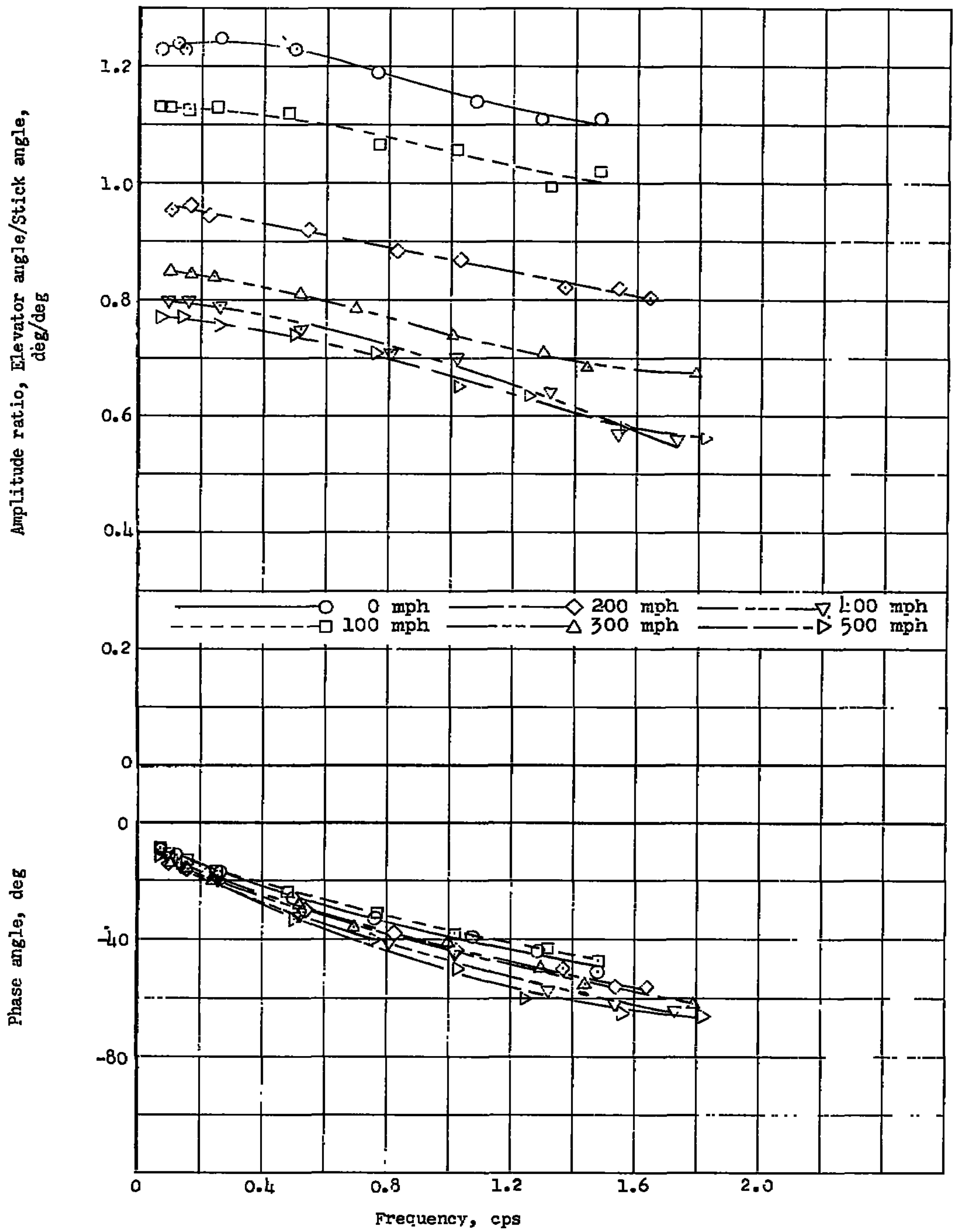


(c) Stick amplitude, $\pm 1\frac{1}{2}^{\circ}$.

Figure 10.- Continued.



(d) Stick amplitude, $\pm 2\frac{1}{2}^{\circ}$.

Figure 10.- Concluded.

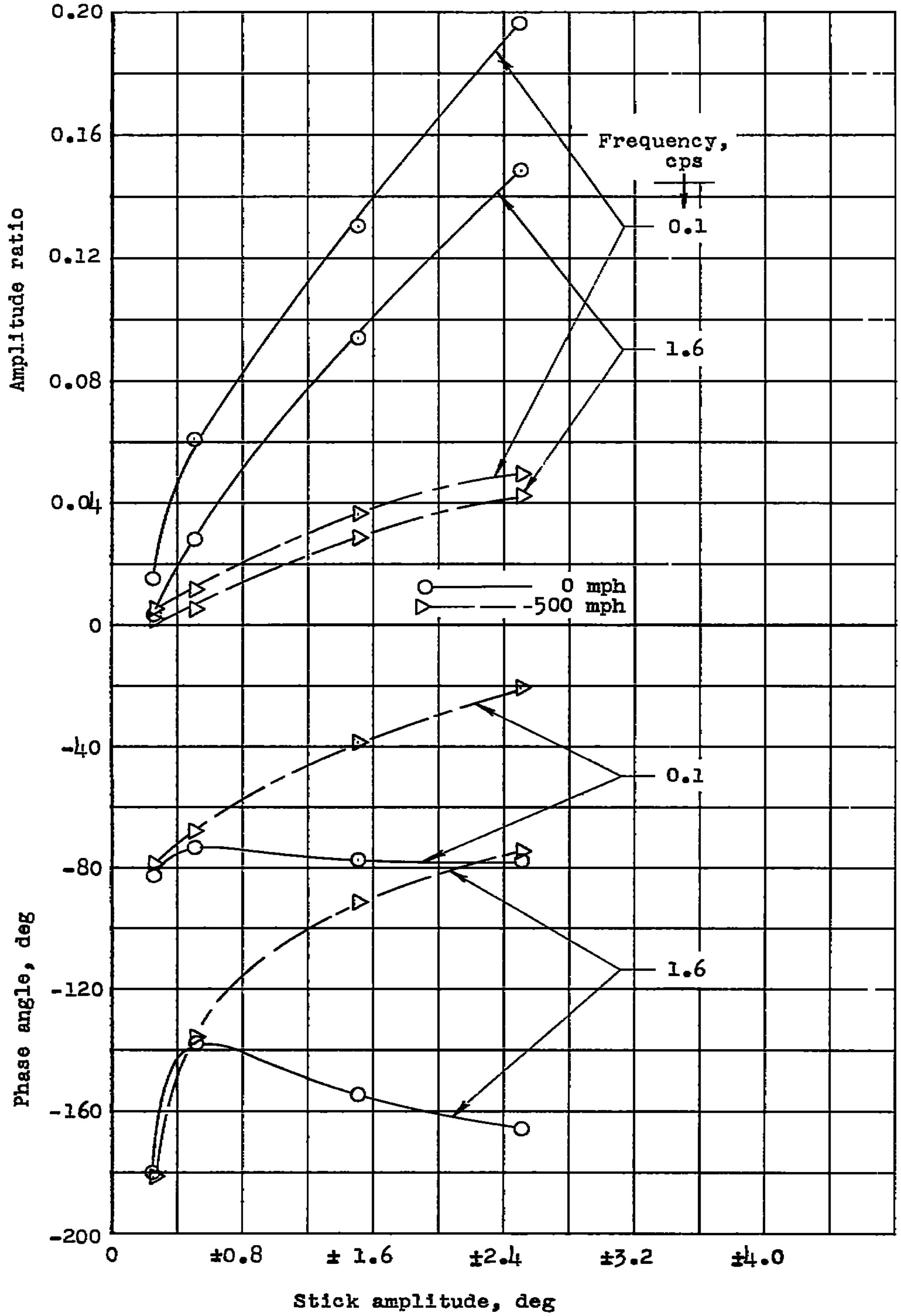


Figure 11.- Amplitude ratio and phase angle between elevator angle and stick force as a function of the amplitude of stick motion.

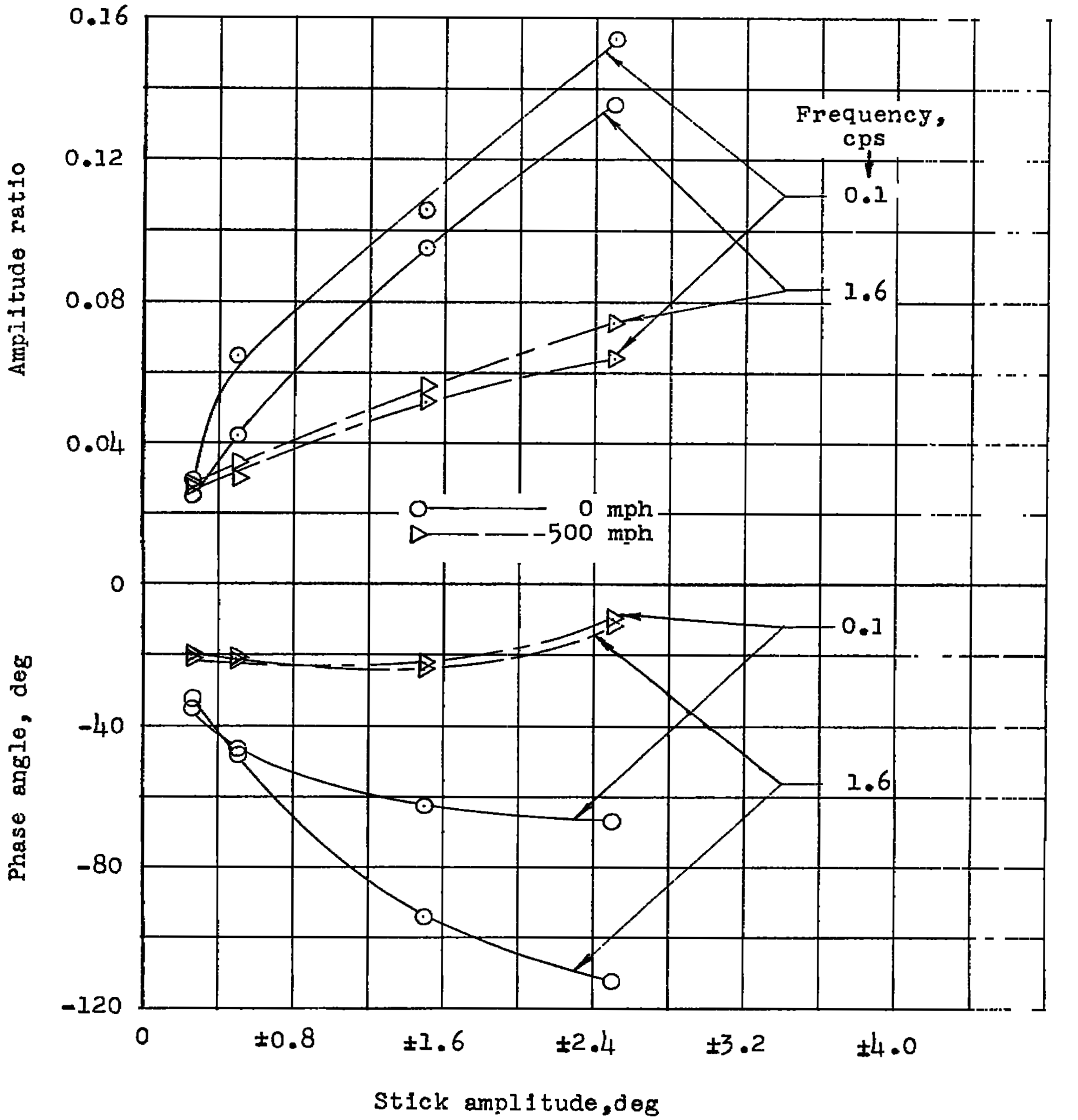


Figure 12.- Amplitude ratio and phase angle between stick angle and stick force as a function of the amplitude of stick motion.

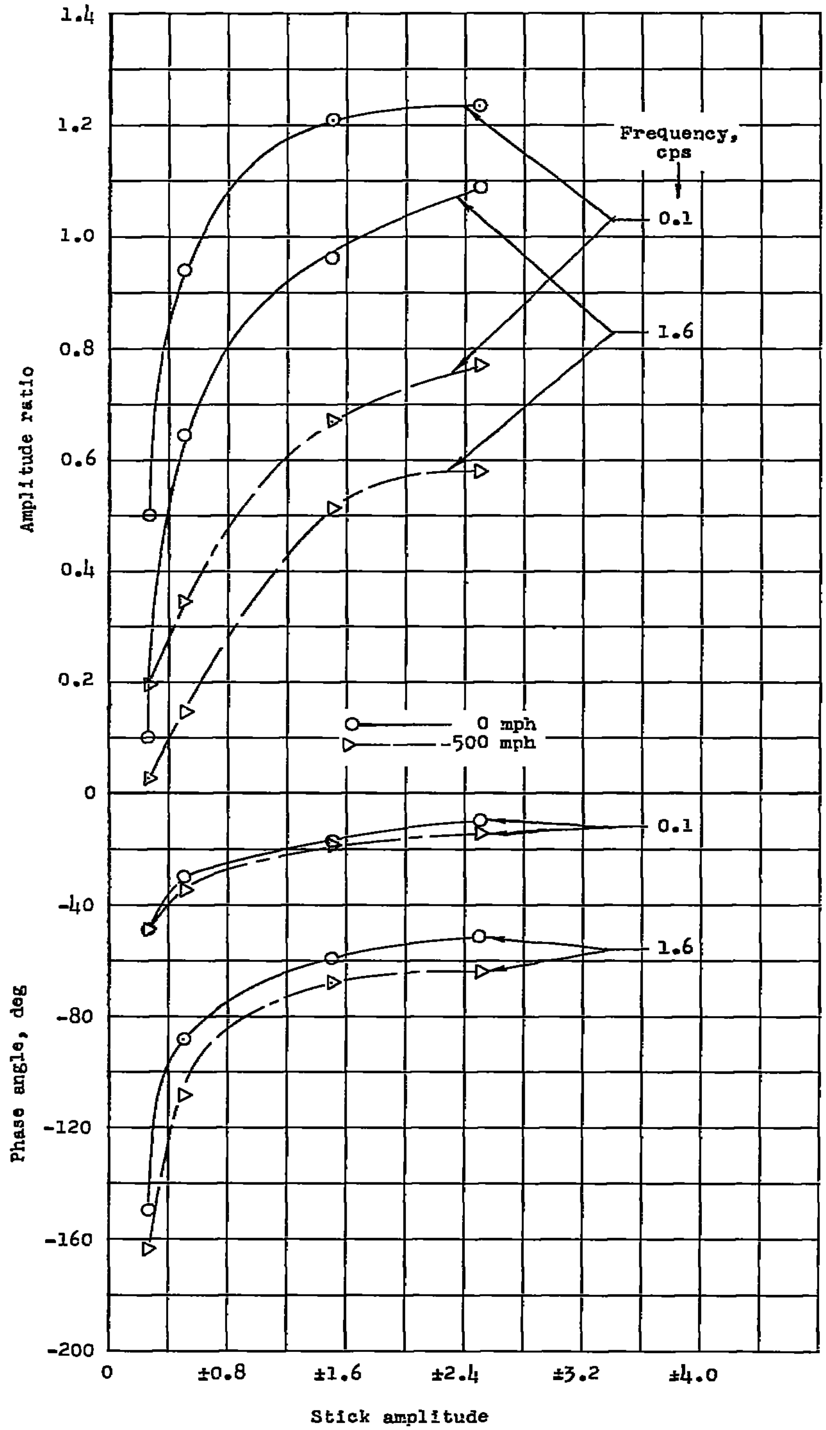
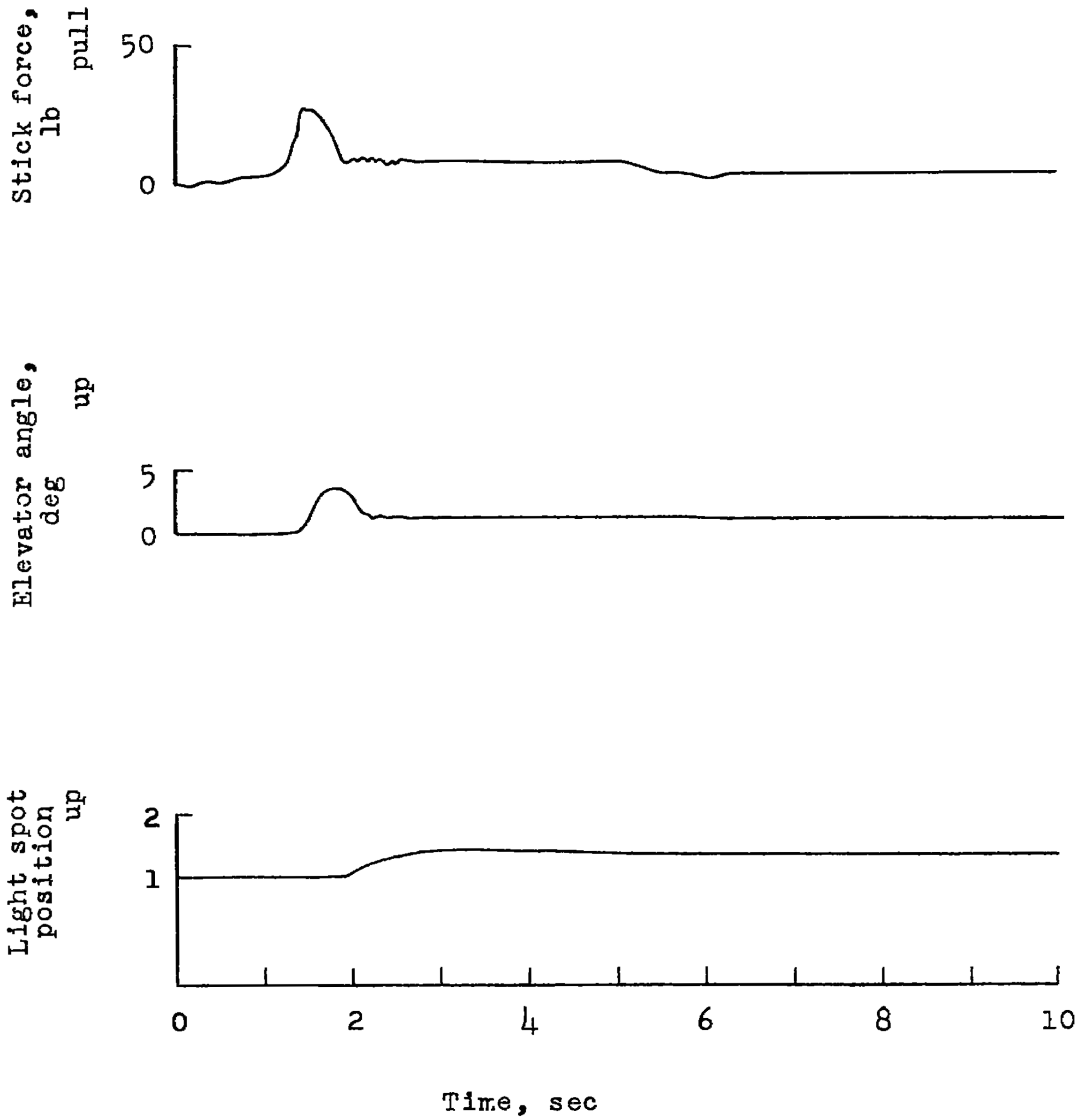
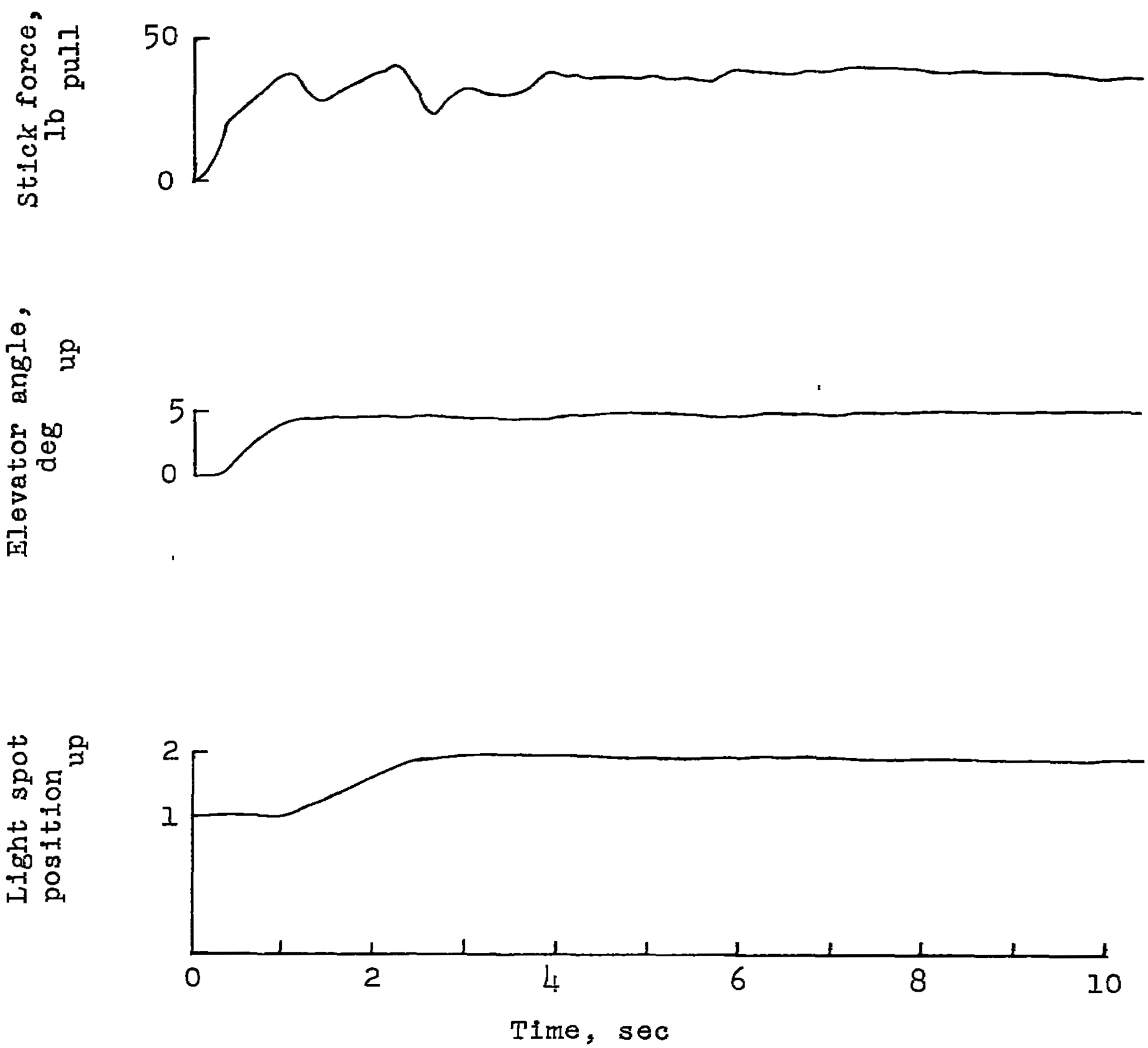


Figure 13.- Amplitude ratio and phase angle between elevator angle and stick angle as a function of the amplitude of stick motion.



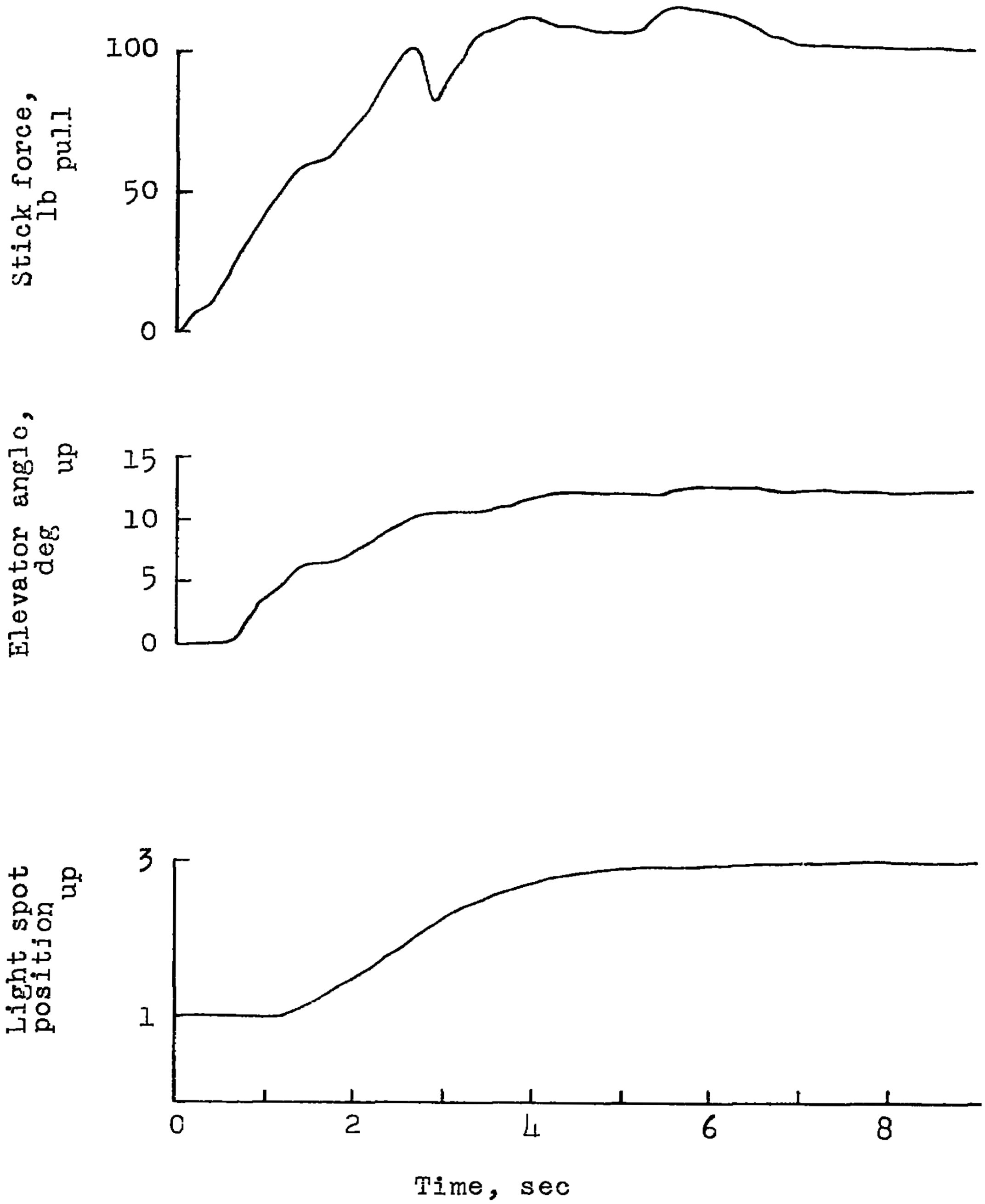
(a) Small elevator deflection.

Figure 14.- Typical records from simulator tests.



(b) Medium elevator deflection.

Figure 14.- Continued.



(c) Large elevator deflection.

Figure 14.- Concluded.

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